

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

# TECHNICAL MEMORANDUM (NASA)4

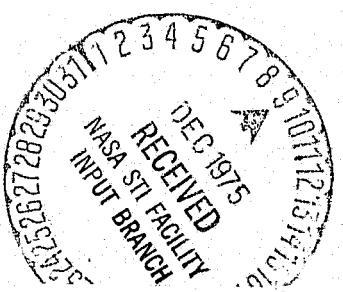
## SIMPLIFIED OMEGA RECEIVERS

Circuit details are presented for a low cost OMEGA receiver being developed for general aviation use. Some novel processing methods, not used in commercial systems, have been demonstrated in experimental bench processors. An airborne model is being designed.

By

Ralph W. Burhans  
Avionics Engineering Center  
Department of Electrical Engineering  
Ohio University  
Athens, Ohio 45701

(NASA-CR-145860) SIMPLIFIED OMEGA RECEIVERS  
(Ohio Univ.) 70 p EC \$4.50 CSCI 17G

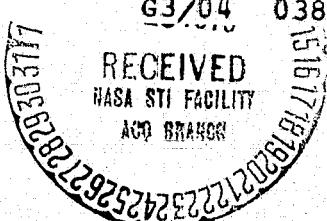


Unclassified  
03894

March, 1974

Supported By

National Aeronautics and Space Administration  
Langley Research Center  
Langley Field, Virginia  
Grant NGR 36-009-017



## TABLE OF CONTENTS

	<b>PAGE</b>
INTRODUCTION	1
BACKGROUND	4
OMEGA FUNDAMENTALS	5
RECEIVING ANTENNAS	8
PREAMPLIFIERS	9
OTHER INPUT CIRCUITS	10
ACTIVE CERAMIC FILTERS	11
FILTER BANDWIDTH CONSIDERATIONS	13
OTHER FILTER TECHNIQUES	14
LIMITER AND PRODUCT DETECTOR	15
ZERO CROSSING DETECTOR	17
STRONG SIGNAL MONITOR	18
ULTRA SIMPLE PHASE AND AMPLITUDE MEASUREMENTS	19
ENVELOPE DETECTORS FOR RECEIVER STARTUP	20
RECEIVER CLOCK	21
HOUSEKEEPING TIMER CIRCUIT	23
SIMULTANEOUS PAIR PHASE MEASUREMENTS	25
PHASE MEASUREMENTS BY DIFFERENCES FROM INTERNAL CLOCK	27
BIT PROCESSING PRECISION	29
PHASE COUNT DISPLAY METHODS	30
LANE COUNTER, POSITION, AND DIRECTION DISPLAY	31

## TABLE OF CONTENTS (CONTINUED)

	PAGE
OMEGA NAVMAP DISPLAY	32
POST INTEGRATION OF PHASE COUNT	33
LOCAL AREA NAVMAP SOFTWARE	34
EXPERIMENTAL RESULTS AND THE FUTURE	36
ACKNOWLEDGEMENTS	38
REFERENCES	39
SIMPLIFIED OMEGA RECEIVERS, FIGURES 1 THROUGH 29	40

## INTRODUCTION

A worldwide navigation resource based on widely separated very low frequency transmitting stations will be an operational reality for the northern hemisphere by mid 1974. Within a few years global coverage will be complete, when international agreements are finished for the remaining three of the 8 transmitting stations. This is the OMEGA VLF system based on accurate synchronization of transmitting stations for providing time or phase difference hyperbolic grids virtually anywhere on the surface of the earth.

The electronics problem of providing low cost hardware usable with this system has not been of any particular concern because present developmental users have been largely military and commercial transport systems where processing hardware economics are not a major item. The little guy, in terms of the general aviation pilot, the small boat operator, or perhaps even the free balloonist and backpacking explorer of the arctic tundra might become potential customers for OMEGA sets on a worldwide basis if the cost and complexity of present receivers could be reduced by an order of magnitude.

This report presents the details of some simple methods for providing OMEGA navigational information starting out with the receiver problem at the antenna, and ending up with informational display and housekeeping systems based on some unique 4 bit data processing concepts. It is believed that the principles outlined here could eventually result in OMEGA receiver devices with less complexity than a color TV set, even without further development of large scale integrated circuits by merely using what is already available in analog IC, TTL, or CMOS circuits. Portable devices operating on a single voltage low drain battery pack with CMOS processors or more conventional systems using a single 5 volt power supply are

possible.

The design concepts outlined here express a minority philosophical viewpoint away from the tendency for excess decimalization and computer processing for sometimes questionable operator convenience prevailing in many other instrument systems. The idea that simpler is better is stressed when possible, with an emphasis on direct binary manipulation at a minimal bit level. A sophisticated computer processor is not really required to solve the basic problem of long range timekeeping for OMEGA.

Navigators have been interested in accurate timekeeping for centuries. In 1660, Christian Huygens almost succeeded in making a seagoing pendulum clock with a clever design which failed due to the lack of a stable platform. The British government in 1714 offered the "Longitude Prize" to anyone who could provide the Admiralty with a clock capable of determining longitude. The prize was £10,000 for  $1^\circ$ , £15,000 for  $40'$  of arc, and £20,000 for  $30'$  of arc. A stipulation was that the clock must be used over a long range voyage from London to the West Indies, and the clockmaker had to demonstrate that it could be produced in quantity. In 1759 John Harrison (1693-1776) succeeded in making a chronometer which eventually claimed the prize providing an accuracy of 3 seconds a day or about 1 part in 28,800. At the present time, quartz crystal time base wrist watches provide this precision and low cost electronic instrument systems may typically have crystal clocks with 1 part in  $10^7$  precision. Atomic clocks are the ultimate in stability providing errors even less than 1 microsecond per day. The basis for navigation has not changed much over the centuries, but the navigation errors have been reduced from 60 nautical miles to 6 meters in the best of modern systems. The OMEGA system depends on very accurate timekeeping at the transmitting source with the user keeping track of time differences over short intervals with

respect to his local quartz "wrist watch".

A complete review of all the historic OMEGA processing methods and those in present use would require a booklength thesis beyond the scope of this paper. The discussion emphasizes what are viewed as the simpler concepts with some comparisons, where appropriate, with alternate methods used in present commercial receiver systems.

The report starts out with some background information on OMEGA fundamentals leading into the receiver antenna problem and front end filters. From there the problem of limiters, zero crossing detectors, and signal envelopes is developed. Internal timing circuits, phase counters, lane position displays, signal integrators, and software maping problems are then presented. The report ends up with some results on experimental bench processors using the 4 bit methods described.

## BACKGROUND

In 1971, aviation consultant George Litchford suggested to NASA that a university program of research and development on air traffic control problems for the general aviation community was needed to develop some alternatives for the future. His major suggestion involved the concept of a nationwide VLF navigation grid which ultimately might be simpler than ever larger numbers of line of sight facilities like VHF and UHF stations. A broad ranging program was initiated involving Professor Dunstan Graham at Princeton on flight dynamics, Professor Robert Simpson at MIT on air traffic control systems, and Professor Richard H. McFarland at Ohio University on avionics. The program was monitored by Mr. William Mace, deputy director of the Flight Instrumentation Laboratory at the NASA Langley Field Research Center, whose work was also concerned with many general aviation problems.

In 1972, a major thrust of this NASA Tri-University Program in Air Transportation was aimed at OMEGA-VLF techniques. The work at Princeton was involved with problems of flight path dynamics of using sampled data positioning systems, the effort at MIT was aimed at systems problems from the pilot-user standpoint, and the work at Ohio University was directed towards development of truly low cost electronic methods for OMEGA receivers. This report is a summary of the results to date on the avionics problem of a Simplified Omega Receiver suitable for general aviation use.

## OMEGA FUNDAMENTALS

The OMEGA low frequency system in development for almost 20 years, will provide a global navigational grid with  $\pm 1$  mile or better precision in most situations. At the present time, transmitting stations in Norway, Trinidad, Hawaii, North Dakota, and Japan provide nearly full Northern Hemisphere coverage. In the near future, stations near Madagascar, Argentina, and Australia will complete the worldwide network. Transmitting stations are owned and operated by participating governments with international cooperation. The system has potential usefulness for even the smallest boat and aircraft but the present phase processing hardware costs start at about \$4K for the simpler receivers and typically run \$50K for sophisticated computer processors with Lat-Long and multiple waypoint range readouts.

The OMEGA system is somewhat similar to LORAN but longer range, providing hyperbolic isophase contours or Lines of Position (LOP) between stations. Because of the wide separation of transmitting stations on a spherical earth, the resulting grid appears to be nearly straight line segments for a hundred miles or so on a typical local navigation usage as illustrated in Figure 1. This chart shows the LOP's for 10.2 KHz constant phase difference produced by station pairs, A-B, B-C, and C-D, (A-Norway, B-Trinidad, C-Hawaii, and D-North Dakota).

Stations transmit in a time multiplexed format illustrated in Figure 2 on 10.2, 11.33, and 13.6 KHz. In principle, LOP's are determined by measuring and temporarily storing phase information from each station and intercomparing their differences through analog or digital loop systems with a local reference phase locked to one of the stations. A long integration time up to 2 minutes, smooths the data readout for use at low navigational velocities.

Differential corrections applied from a nearby ground monitor to the user via a radio link, or correction tables are used to compensate for the diurnal changes due to propagation at these very low radio frequencies. Propagation changes can vary as much as a full LOP or about 8 miles at the 10.2 KHz frequency over a 24 hour period. At any given time, the isophase grid is changing quite slowly with respect to the velocity a navigator may be using in his vehicle. The grid may be thought of as a rubber-like map stretching slowly over the earth surface, back and forth as the earth rotates every 24 hours. The stretch or change in the grid structure is quite predictable and tables are published for areas covered by the OMEGA system. Minor problems are created at local sunrise and sunset due to somewhat more rapid phase changes. Solar flares also sometimes produce SID's (Sudden Ionospheric Disturbance) which may distort the grid many miles for a short period of time. The general experience is that users can anticipate a worst case error of  $\pm 2$  nautical miles at night and usually can do much better when good correction data is available from tables or ground based monitors.

When navigating with aircraft at long ranges from a VOR station or ground based surveillance radar, the precision of OMEGA is usually better than these present systems can provide. The advantage of OMEGA is that it is worldwide and does not require an extensive ground based system for accuracies in the  $\pm 1$  nautical mile range. Furthermore, it can be used in mountainous regions where VOR and radar coverage is restricted, or virtually anywhere at sea, well out of range of line of sight facilities.

The problem at present is that most potential users and hardware producers are unaware of OMEGA, particularly the relative simplicity of some signal processing steps required to obtain useful navigation information. This article will further develop some useful low cost

circuit methods which have been applied to experimental OMEGA receivers. In these simplified design considerations a single 5 volt power supply operates both the analog amplifiers and digital TTL or CMOS circuits.

## RECEIVING ANTENNAS

The transmitted OMEGA signals are derived from atomic clocks with very high precision in time and phase stability synchronized with precision of  $\pm 1$  part in  $10^{11}$  per day (about  $\pm 1$  microsecond per day errors). Ten KW and large transmitting antenna systems typically result in signal levels of 300  $\mu$ v at 800 nautical miles across the input to a high impedance preamplifier with a short receiving whip antenna (20 foot wire). The atmospheric noise level at 10.2 to 13.6 KHz on a short wire antenna is typically quite high, 1  $\mu$ v/Hz of receiver bandwidth.

A short whip or wire antenna is by far the simplest to install but suffers from locally generated precipitation static in blowing snow or rain, and is non-directional with respect to nearby thundershower spherics and other local interference. A loop or crossed pair of loops can reduce local noise in many applications, but requires more processing for the phase ambiguity introduced depending upon the direction to the transmitting source. Much work has been done and many methods are proposed for reducing antenna noise problems, all of which tend to increase the cost of present receiver systems. A commercially available crossed loop antenna system for VLF can cost about \$1K. If our goal is eventually a receiver-processor system for OMEGA with a total cost of less than \$1K, some much simpler approaches to this problem are required. A single wire antenna appears usable in most cases if proper attention to the details of the preamplifier and filter assembly is given.

## PREAMPLIFIERS

A preamplifier with high input impedance is used with sufficient gain to overcome the noise of common operational amplifier networks applied to ceramic or mechanical high Q bandpass filters. A preamplifier with a voltage gain of X 10 (20 db) is desirable with an input noise factor less than 0.1  $\mu$ v/Hz. A more than adequate amplifier is obtained from a diode protected dual gate MOSFET operated in the mode illustrated in Figure 3. Here the whip antenna is coupled through an isolating capacitor to the control gate, and the preamplifier is physically located at the antenna end. The MOSFET drives a transistor amplifier, transformer coupled through a wide band transformer of the DIT variety. The low impedance output line from the transformer couples the signal to the receiver and the 5 volt power for the preamplifier operation is supplied over the same cable. Thus a single coaxial cable of several hundred feet can be used to separate the main receiver from the antenna-preamplifier. A photograph of one of this type of preamplifier assemblies is shown in Figure 4.

## OTHER INPUT CIRCUITS

A very high quality toroidal matching transformer is used in some commercial receiver systems directly at the antenna with a low impedance output line driving a more conventional low impedance receiver input circuit. This requires more gain and lower noise level in the receiver to make up for the transformer attenuation. Other preamplifier circuits using JFET's or bootstrapped bipolar transistors to provide input impedance of greater than 500K ohms are adequate for VLF use with wire antennas. With loop antennas, a low noise circuit is required because a lower output voltage is available at a lower impedance level.

A relatively high atmospheric noise level is usually a limiting factor in VLF receiver input circuits. MOSFET's without internal input protection are not recommended because of a tendency to burn out on strong spherics. Matching transformers and other input circuits sometimes use a neon bulb for high voltage discharge protection. However, neon bulbs can create additional problems, sometimes increasing the noise due to their time dependent discharge characteristics.

In balance, active input impedance converters with bipolar transistors or diode protected MOSFET's appear to be more than adequate and are usually a lower cost approach for short wire antenna systems. One of these active input circuits has been in continuous use for several years on a roof top wire antenna system with a local exposure rate of about 35 thundershowers per year.

## ACTIVE CERAMIC FILTERS

The low Z output line of the preamplifier directly drives split ring ceramic filters which operate like high impedance mechanically coupled tuning forks. These ceramic filter units are potentially available at quite low cost if sufficient demand for them in the VLF-OMEGA market can be created. A single filter unit followed by a gain block of 10 db also results in the first stage bandwidth reduction of Figure 5. These filter units have small spurious high frequency responses which are removed with the active multiple feedback network of Figure 6. The lowpass filter is designed with a cutoff of 4 to 5 times the operating VLF frequency, based on an output impedance of about 25 K ohms for the ceramic filter as the input source to the filter. The ceramic filters are "tuned" to the exact OMEGA center frequency with series capacitors for which they have a very low sensitivity factor of about 0.1 Hz/pf. Each amplifier is designed for low phase error or exactly 180° at the frequency of interest. Very similar amplifiers may also be used on other VLF channels such as for the high power communications channels around 17.8 KHz and the time-frequency standard station WWVL or 20 KHz or WWVB on 60 KHz.

The system bandwidth is further reduced in a second stage nearly identical to the first stage filter. This results in the very narrow bandpass curve of Figure 7 with good skirt selectivity. The two stage filter is designed for an overall gain of slightly greater than 20 db for a whip antenna usage. For OMEGA use it is often desirable to have a two channel receiver or filters for both the 10.2 KHz and 13.6 KHz frequencies as shown in Figure 8. Here a single quad LM 3900 provides both pairs of amplifiers with reasonably good isolation on a simple layout illustrated in the front part (antenna terminal or preamp output) of the

assembly photograph of Figure 9. The very early narrow bandwidth reduction characteristics in two stage jumps results in reasonably good performance even in noisy situations with a whip antenna.

## FILTER BANDWIDTH CONSIDERATIONS

For navigation usage measurable signal levels from at least 10  $\mu$ V to 1000  $\mu$ V in a 15 Hz bandwidth using a whip antenna, are desired for an adequate VLF receiver. In most cases we would need to receive a minimum of 3 OMEGA stations thus providing at least two station pairs for navigational grid determinations. A bandwidth of around 15 Hz allows the filter a relative short time to build up to signal level as opposed to a 1 Hz or narrower filter which would not operate well on the typical 1 second on time burst of the signal format shown previously. (Figure 2) A very narrow band filter of 1 Hz will also have problems of excess ringing when excited by the predominantly higher frequency components of the wide band antenna noise due to spherics.

## OTHER FILTER TECHNIQUES

Commercial OMEGA receiver systems use a wide variety of methods including ceramic filters, mechanical filters, multiple stage LC filters, and superhet systems. A superhet method wherein a local oscillator is mixed with the input signal to generate a 1000 Hz IF is used in some classic OMEGA receivers. An advantage from the filtering standpoint is that a Q of 100 represents a 10 Hz bandwidth at 1 KHz whereas a Q of 1000 would be required in TRF methods at 10.2 KHz for the same bandwidth. IF methods also create additional filtering problems involving the image frequencies which results in more complex front end circuitry. A 1 KHz IF system is particularly useful for all analog circuit methods. TRF methods are generally better for digital processing which depend upon generating zero crossings directly at the signal frequency. The advent of reasonably priced high Q ceramic and mechanical filters in the VLF range makes these TRF methods attractive at the present time.

Early application of filtering immediately following impedance conversion with minimal preamplifier gain is desirable. Both mechanical and ceramic filters have non-linear spurious response behavior related to the sound effect of banging a tuning fork too hard. Thus, excitation of the filter with a relatively low level signal helps reduce undesirable responses as opposed to filtering at a high preamplifier gain level. In general, application of filters in successively narrower bandwidth steps is desirable to aid in reducing noise. Some commercial receivers carry this to extremes of 5 or 6 stages. A two stage ceramic filter system appears adequate and is potentially quite low cost compared to alternate methods used in many present receivers.

## LIMITER AND PRODUCT DETECTOR

A primary goal here is the phase measurement of the signal and a means for determining the zero crossings of the signal frequency. A standard FM limiter-detector integrated circuit package normally used at 10.7 MHz, turns out to provide both good limiting properties with no phase error as well as a means of measuring signal amplitude. Some amplitude information is desirable so that the local receiver clock may be easily synchronized to the transmitted OMEGA format by using the strongest station burst for lock-up when the receiver is first turned on. The circuit is shown in Figure 10. The bandlimited output for phase information is taken just ahead of the multiplier. A reference voltage is also available on the same chip for use in a comparator with the DC level of the reference the same as the average DC level of the signal output.

The multiplier provides a synchronous product detector using the unlimited filter output driving an emitter follower to isolate the relative high filter output impedance of 1000 ohms or so from the multiplier input terminal. This envelope detector has a characteristic such as illustrated in Figure 11. The overall gain from antenna input to limiter output is 104 db for this graph. Thus the threshold starting around 3  $\mu$ v is about 10 db lower than the normal atmospheric noise level at the antenna in this 15 Hz receiver bandwidth. This results in a compression action or hard limiting wherein signals from 10  $\mu$ v to 10,000  $\mu$ v all produce about 1.5 volts peak to peak amplitude signal output for phase measurements.

The envelope detector output level changes of typically 1 volt swing on a 300  $\mu$ v signal provides a very satisfactory initializing envelope pulse for receiver start-up. It is

important that the overall phase shift from antenna to limiter output be low. The front end system as illustrated combining Figure 3, Figure 8, and Figure 10, provides exactly  $\pi$  or  $2\pi$  depending upon which of the zero crossings is chosen for further phase processing.

## ZERO CROSSING DETECTOR

Still more system gain is used to provide clean square wave edges for further use.

The limiter output signal drives the comparator and edge detector circuit of Figure 12.

A small amount of decoupling at the limiter output (Figure 10) is needed to prevent a slight tendency for regeneration due to the very high frequency gain in the limiter circuit (the limiter provides 60 db gain). The phase shift introduced by the decoupling is smaller than the least significant increment of phase measurement desired, or smaller than  $3^\circ$  at 13.6 KHz. The comparator drives the edge detector differentiator which provides a simple means of generating pulse trains for the leading edge zero crossings of the original signal.

The comparator circuit provides an additional 20 db or more of compression, resulting in measurable square waves for signals down to  $1\mu v$  at the preamp input.

## STRONG SIGNAL MONITOR

Figure 12 also illustrates the use of the envelope output for generating an auto start pulse at the end of the strongest signal burst. For a major portion of North America, the 10.2 KHz signal from D channel at North Dakota will provide a strong signal level of greater than 100  $\mu$ v at a whip antenna. The envelope output is fed to a comparator with a threshold adjustment to provide a pulse proportional to the length of the envelope output. The width of the D channel signal as seen by the 15 Hz bandwidth filter will be around 1200 ms but slightly delayed due to the filter bandwidth and the envelope filter round off capacitor of Figure 10 (2 mfd). A monostable(74121) adjusted for an output width of about 1150 ms is compared in a NAND gate with the comparator envelope output. This results in a short pulse, 50 ms or less, near the end of the D channel signal. The slight delay and exact width are not important since the receiver synchronizing circuit to be described later, will tolerate a 50 ms error. This auto start pulse is used for later sync. of the local receiver clock. The same comparator circuit also drives a visible LED indicator and keys an audio oscillator for qualitative monitoring of the strongest signal. The audio monitor is quite useful to tell the pilot or navigator that his receiver is indeed receiving signals. Both the audio signal burst and the LED may be observed flickering between signals on noise pulses but a strong indication could be obtained on the D channel virtually anywhere in the USA depending upon the adjustment of the threshold control. The auto start pulse is only required once for initial startup when the local receiver timer takes over, but is continually operating to provide these qualitative signal level monitors. Using a combination of both width and amplitude discrimination provided by this circuit, it should be possible to generate synchronizing events for other stations in the OMEGA system within 1500 nautical miles or farther from the station chosen.

## ULTRA SIMPLE PHASE AND AMPLITUDE MEASUREMENTS

At this point we have provided information or signals proportional to phase and amplitude. The limiter output phase may be compared to a local signal synthesized from a good crystal clock or even to a signal generator, using only an oscilloscope for display. Elementary Lissajou figures of the phase difference may be observed directly on the stronger signals. While this is useful for laboratory demonstrations it is hardly suitable for navigation purposes.

Similarly, the amplitude information of the strongest signal envelope may be used as a clock which "ticks" every 10 seconds. A local crystal clock with count down chain to 10 seconds may be compared in phase position with respect to the OMEGA transmitted signal and this averaged over a 24 hour period provides quite accurate estimates of the local clock offset and aging rate. Time, accurate to a few milliseconds, may be estimated by correcting for the propagation delay from the transmitting station, and using diurnal corrections from tables. The present OMEGA format is such that station A at Aldra, Norway transmits on 10.2 KHz starting on the 57th second (and 7, 17, ....etc.) of each minute with respect to UT. Announcements of future changes in the precise timing offset compared to the international atomic second appear in "Notices to Mariners" and other publications of the Hydrographic Office of the U. S. Department of Defense.

## PROBLEMS WITH ENVELOPE DETECTORS FOR RECEIVER STARTUP

There will be locations on a world wide basis where all signals received are at a relatively low level. In this case, amplitude-time discrimination with a simple envelope detector may not be adequate for receiver startup. Another method is a 90° phase detector operating in parallel with a phase locked loop used for the primary phase detection. This provides higher sensitivity for signal amplitude discrimination. A quite complex solution to the problem, used in some of the more sophisticated OMEGA processors, involves a complete cycle matching of the OMEGA sequence. A shift register word generator, programmed to agree with the OMEGA sequence spacings of Figure 2, combined with the phase measurement of all signals, is then compared to the filtered incoming signal and the clock rate advanced or retarded in a phase lock loop to match the two signals. Sooner or later the system will lock up on the correct spacings of time slots with at least two weak signals detectable in the sequence.

For really low cost systems there is presently no easy solution to this problem other than to restrict the use of OMEGA such that one station is 1500 to 2000 nautical miles away and always available for automatic startup considerations. There is still one other technique involving observation by the receiver operator of the signals on an oscilloscope or signal strength LED indicators. The operator then carefully tries to match the internal receiver clock position with what he observes on the indicators. This is adequate for shipboard use but a semi-automatic method would be much more desirable from the standpoint of the general aviation pilot or small boat operator who may not be skilled in these instrumental measurement methods and who cannot afford the extra expense or hasn't the time to bother.

## RECEIVER CLOCK

All OMEGA receiver systems require some form of internal clock to provide a means of telling which station is being measured at a particular time. A variety of methods are used, most of which also provide internal housekeeping and phase measurement references from the same clock. The more sophisticated processors use cycle matching systems with a single reference oscillator operating at a high enough bit rate to generate all possible signals of interest from 0.1 Hz, the time interval of one complete OMEGA sequence, to 10.4448 MHz which is a 10 bit clock rate for a 10.2 KHz signal.

$$(2^{10} \times 10,200 = 10.4448 \text{ MHz or better than } 1/1000 \text{ of a 10.2 lane})$$

Professor Pierce of Harvard in designing the original system, chose 408 KHz as the least common multiple frequency of all the signals of interest. In the simpler receivers, one or two of the 3 channels available are used. If we consider 10.2 KHz and 13.6 KHz, the least common multiple frequency is 40.8 KHz ( $10.2 \times 4 = 13.6 \times 3 = 40.8$ ). A 4 bit 40.8 KHz signal would require a clock rate of  $2^4 \times 40.8 = 652.8 \text{ KHz}$ . Four bit data processors are usually simpler to implement than 7 or 8 bits required of decimal lane counters with centilane indicators for 1/100th of a 10.2 lane or 1/100th of a 13.6 lane. Thus if we are trying to use a common clock frequency, it is of interest to consider the very minimal processor rate required for a specified bit precision in the final output displays. Binary systems require no further conversion for direct use of the output data. Thus a 4 bit D/A output of 1/16th is as good as a 1/10th lane indicator and requires less digital logic circuitry to implement. A 4 bit 40.8 clock rate will provide 1/64th of a lane resolution at 10.2 KHz or effectively 6 bits. Other considerations of the phase measurement round off error problem,

which will be discussed in a later section of this report, show that a  $40.8 \times 2^4$  rate is adequate to supply final output phase information at a 1/10th or somewhat better precision for 10.2 KHz lanes. The 652.8 KHz clock frequency is actually easier to implement at a higher crystal frequency of say  $10 \times 652.8 = 6.528$  MHz because of better oscillator stability and lower crystal costs. Thus a clock at 6.528 MHz or some other simple integer multiple of 652.8 KHz is the first requirement of a timer system for a simplified binary processing OMEGA receiver.

## HOUSEKEEPING TIMER CIRCUIT

A housekeeping timer system (HKT) based on this thinking is illustrated in Figure 13. This starts out with a standard commercial crystal oscillator package at 6528.000 KHz which has a short term aging rate of less than  $1 \times 10^{-9}$  and is trimmable to within  $1 \times 10^{-7}$ . The precision can be worse but as long as we need some kind of crystal oscillator it is probably wise to start out with one of this quality. Direct division by 10 supplies the basic counting rate of  $16 \times 40.8$  which will be used in the later phase detector circuits. Division by other combinations of integers provides all the processing signals needed in the form of binary frequencies, 25.6 Hz, 12.8 Hz, . . . . down to 0.1 Hz or the basic OMEGA sequence rate. An octal decoder generates a gate proportional to time slot position and NAND gates (not shown) generate the timing functions illustrated in Figure 14. In order to start this circuit in synchronism with the OMEGA sequence, a uniform time slot scheme such as illustrated in Figure 15, is used. Similar methods are used in some of the lower and medium priced OMEGA receivers. Uniform length time slot read and write intervals are far easier to generate than cycle matching to the OMEGA sequence. If a delay of 1.25 seconds/4 is used after the station selected for startup, all of the uniform sample intervals occur when the stations shown are transmitting simultaneously on 10.2 and 13.6 KHz. A more detailed illustration of the delays and spacing of the time slot sample intervals of interest is shown in Figure 16. This is illustrated for the case where D on 10.2 KHz has been chosen for the startup pulse provided by Figure 12. If we choose any other station for startup, a similar timing diagram may be computed with the same T/4 delay before start.

The semi-automatic startup circuit is illustrated in Figure 17. Here a no-bounce push button circuit is used to provide a reset signal. The reset button is activated after

receiver turn on and after the threshold control for signal envelope is adjusted for blinking every 10 seconds on the desired signal. This stops the decoder at count zero in the preselected C-D time slot position with D on 10.2 KHz. Within 50 ms of the end of the next D signal, the circuit of Figure 17 latches up and starts all the divider chains of Figure 13 operating. The dividers down to 0.8 Hz are all preset to the complement of the divisor.

When the auto start pulse comes on, they start counting immediately (within 1/6528000 seconds) and the 0.4 stage flips over T/4 seconds later (where T = 1.25 seconds or 1/0.8 Hz).

In order to program for other start points, the position of the desired start on zero decoder output is shifted to the corresponding station pair. Effectively the D channel is permanently wired for startup. Shifting the start time to another channel is only a problem of relabeling the switches and indicators. Figure 18 illustrates the sequence indicator and switches for selecting the station pairs labelled for a start point on D channel at 10.2 KHz for the zero count of the decoder position. The sequence indicator is useful to monitor where the receiver is, at a particular time and also check to see if the D channel light comes on when the envelope blinker light is operating. Once started the circuitry continues to operate until it is shut down or the reset button is pushed for a new start. The circuit will operate for more than 24 hours continuously with no time slot sampling error overlap if the input clock frequency is set to within  $1 \times 10^{-7}$  or so.

More sophisticated housekeeping timer circuits with shift register methods are used in many commercial receivers. The direct divider-decoder timer illustrated in Figure 13 is about as simple as possible within the limitations of readily available IC logic and MSI circuitry. Any other clock frequency chosen for other phase detection schemes will require about the same amount of hardware for these lower cost uniform time slot sampling methods.

## SIMULTANEOUS PAIR PHASE MEASUREMENTS

Further inspection of Figure 15 shows that these are simultaneous transmissions from different station pairs in each time slot. It is of interest to consider the possibility of a phase measurement method where the phase difference between these two frequencies (10.2 and 13.6 KHz) is measured in each time slot with respect to each other without using a reference oscillator. For example, if the 10.2 KHz zero crossings are arranged to always turn on an RS flip-flop and the 13.6 KHz zero crossings always turn it off, a series of gate or on-off intervals are generated as in Figure 19. Illustrated here is the case where the 10.2 and 13.6 edges are in phase at an arbitrary start point with the width intervals measured as a count total where the count rate is  $16 \times 40.8$ . The result is a count-width interval which repeats every 3 cycles of 10.2 and every 4 cycles of 13.6. If the phase of the 13.6 signal is arbitrarily retarded or occurs later with respect to the same relative 10.2 edge, then the gate intervals double in width at the point where the phase shift is equivalent to one 40.8 KHz phantom lane change. Thus a repeating 40.8 KHz least common multiple frequency lane change is obtained by simultaneous use of 10.2 and 13.6 edges. It is convenient to divide the output width interval count by 3 to obtain a binary count where the count total varies from 16 to 32 for one 40.8 lane change. Thus we can arbitrarily define a count total of  $16 = 0^\circ$  phase and  $32 = 359^\circ$  phase at 40.8 KHz. The difference  $32 - 16$  gives 16 counts for a full 40.8 lane. The bias of 16 at zero phase is easily subtracted by using only a 4 bit register in the final output count indicator. The overflow of 16 disappears out the end of the last counter stage.

A phase detector scheme which utilizes this method is illustrated in Figure 20. Here the output width intervals are divided by  $3 \times 2048$  to provide 602 milliseconds of averaging

of the 10.2 KHz frequency. The RS flip flop is arranged to operate on the start pulse from the HKT illustrated in Figure 14. After  $3 \times 2048$  of the 10.2 edges, the counter stops and is reset for the next pair. In the meantime a serial count output has flowed out of the output terminal to a 4 bit counter-display which will be described later. The serial count output from Figure 20 is a 4 bit number from 0 to 16 which is the average phase difference of the resulting 40.8 KHz phantom lane or least common multiple frequency generated.

This method is not used in any existing receivers. At first glance it may appear too simple and restricted by the fact that the combination of lanes used for navigation is limited to the simultaneous pairs. Thus adjacent pairs like B-D are not obtained directly. However it is possible to obtain other combinations of lanes provided that measurable simultaneous signals are present in each of the time slots used. This is done by subtraction in up-down counters after or during the simultaneous pairs, using a parallel register gated by the appropriate time slot intervals.

In a major portion of the USA, the simultaneous pairs B-C and C-D can provide usable measurements. B-D may be provided by counting down a parallel register during the C-D interval. Pair A-B is usable in some regions of the eastern United States where the Greenland ice cap does not shadow the reception zone. However at the present time, OMEGA users in most of the rest of the United States and particularly in western regions, are restricted to stations B, C, and D because of excess signal loss from A over the Greenland ice cap.

An advantage of this simultaneous pair phantom lane concept is that of processing simplicity and the internal clock stability is of little consequence in determining the output phase difference. The phase difference measurement is primarily a function of the two signals received and their respective signal to noise ratios.

## PHASE MEASUREMENTS BY DIFFERENCES FROM INTERNAL CLOCK

Methods used in many existing digital processing OMEGA receivers are single and cumulative differences with the internal clock as a reference. In the single differences technique, the differences between the clock and the signals in less than one OMEGA sequence are sequentially subtracted to yield pairs. In the cumulative differences method, the differences between the clock and signal are averaged over more than one OMEGA sequence.

In these methods the clock drift or absolute value of the offset is of importance. A clock with a frequency offset error of  $1 \times 10^{-6}$  at 10.2 KHz will produce a 2 bit error at a 6 bit measurement level when comparing station A with station D in the same sequence, due to the average clock offset in the 3.6 seconds from the A to the D determination. A clock offset error of  $1 \times 10^{-7}$  will obviously do better and produce a 1 bit error at an 8 bit measurement level with the same delay between subtractions. Thus a reasonably good TCXO circuit capable of being trimmed to an offset within  $1 \times 10^{-7}$  can provide a measurement precision of within 8 bits or 1 part in 256 per lane at 10.2 KHz with a delay of 3.6 seconds between the pair subtractions.

The method of cumulative differences can provide high bit precision at the expense of more arithmetic processing and memory capacity. Arithmetic processors at an 8 bit or higher level are used. The same arithmetic processor and memory for all the signal information can also be used to integrate the data readout over any number of time slots depending upon the velocity error tolerable in the end use of the data.

The advent of 4 and 8 bit microprocessors in single chip form, makes these methods attractive for future low cost OMEGA receivers. More conventional circuits using combinations of these methods may involve up to 50 functional IC's and MSI packages for the basic phase processor. Some of the newer MSI chips such as the BCD adder-subtractor can be used to advantage. Integration over multiple time slots is sometimes provided by running average methods using a shift register to shift new data sequentially and add it to previous data in conventional binary addition circuits. Subtraction techniques can also involve the use of up-down counters as opposed to parallel arithmetic processors.

## BIT PROCESSING PRECISION

Some commercial OMEGA receivers use a final output display precision of 1/10th of a 10.2 lane. Thus each output increment of phase represents slightly less than a mile on the pair baseline. The noisiness of the OMEGA raw data generally makes it undesirable to present information to the pilot at a centilane or 1/100th of a 10.2 lane precision. The data, even when averaged over a few time slots will be jumping around too much, particularly if one of the stations of the pair is a weak signal. Thus 1/2 to 1 mile output increments of phase are desirable for navigational use to aid in smoothing the information display for the pilot or navigator.

In order to supply the data readout at this precision it is usually necessary to provide higher phase processing accuracy. Commercial receivers may typically use 8 bits at 10.2 and 13.6 KHz, or 1/256th of a lane. The 4 bit processor methods described in this report use 6 bits for processing and 4 bits for readout providing a readout equivalent of 1/16th of a 10.2 KHz lane. The internal processing is at a 4 bit 40.8 level which is effectively 1/64th of a 10.2 lane. Since cumulative difference methods are not used in this lower cost approach, the 6 bit precision in processing provides sufficient accuracy for a reasonably low quantization error at the 4 bit output level.

## PHASE COUNT DISPLAY METHODS

The 4 bit binary information from Figure 20 can be displayed at the output of a 4 stage counter directly in binary format. Unfortunately most potential users of OMEGA equipment are not happy with raw binary information. Some conversion to more familiar or easier to read information is desirable. A 4 bit D/A used with an external pointer reading indicator or a pen recorder, is one possibility. Decoding the output to a sequential step indicator with 2 line to 4 line, or 3 line to 8 line decoder, is another very simple method. A sequentially decoded output is quite easy to interpret by watching the expected fractional lane position change, up or down, right or left, as the vehicle moves across the lane pair being measured. A circuit which provides these three methods of phase count display is illustrated in Figure 21. This provides a 4 bit D/A, a 2 bit sequential step indicator, and direct 4 bit binary display.

## LANE COUNTER, POSITION, AND DIRECTION DISPLAY

A lane position indicator is similarly a useful navigation aid. A system which will keep track of the number of lanes traversed and the direction of motion is illustrated in Figure 22. This uses a 2 bit comparator circuit to compare the most significant bits at the input and output of the latch of Figure 21 at the selected pair time slot to determine if a lane transition has occurred. When a transition occurs, the lane position display increments up or down one step and the direction indicator shows which way the lane change is going. A momentary preset button may be operated to step the output lane position display to any desired point, going from position 0 to 15 and starting over again on the 16th step. A 16 step lane position indicator will cover about a 32 mile range for 40.8 KHz lanes and a 128 mile range for 10.2 KHz on the station pair base line. This would be useful for local area aircraft navigation aids or coastal area navigation considerations for boats.

## OMEGA NAVIGATION MAP DISPLAY

A proposed method of combining two lane pair indicators into a single navigation aid device is illustrated in Figure 23. This combines part of Figure 21 and 22 for two pairs into a compact OMEGA NAVMAP. In use, the pilot or navigator presets his course with respect to OMEGA coordinates on the course overlay cursor from prepared software or special maps similar to an IFR route navigation chart used in instrument flying. The operator then increments his present known position to the desired starting point on the display and proceeds to move in the direction chosen using an independent direction indicator such as a compass or directional gyro to maintain approximate course heading correctly. He then observes the indicator direction lights operate as long as he is crossing lanes in the proper direction and the cross pointer lines indicate his approximate position. The phase direction decoder shows positions sequentially between lanes for finer resolution of the display.

This display concept is intended for relative use of OMEGA on a short term navigational mission such as an hour flight where the pilot does not need to know the absolute OMEGA lane numbers but is primarily interested in going from some start point to some finish point with respect to the display. The display may also be used for longer range purposes by noting where the cross pointers drop off the edge and presetting ahead. Automatic preset ahead might be provided with additional logic circuitry using the carry and borrow outputs of the 74193 counter of Figure 22. Further sophistication of the display might be possible in switching from high resolution 40.8 KHz lanes to low resolution 10.2 KHz lanes and maintain the same relative position with additional logic and data storage capacity.

## POST INTEGRATION OF PHASE COUNT

An integrator connected between the output of Figure 20 and the input of Figure 21 is useful to smooth the data readout further on noisy signals. The integrator consists of simple shift registers and binary adders arranged to average the previous counts with the present count over any number of time slots. The averaged count output is then fed to the phase counter display circuit on the appropriate time slot command. Multiple time slot integration inherently increases the velocity error. A 40 second integrating time (4 time slots) would imply a 20 second lag in the averaged data or of the order of a mile behind the actual aircraft position flying at 180 knots directly across the lane pair measured. Integration times of up to 2 minutes are used in marine receivers to smooth the data readout for low velocity applications. Shift register storage and binary integration can also be used to smooth the lane transition data source by operating the lane counter from the average of several previous time slots compared to the most current readings.

## LOCAL AREA NAVMAP SOFTWARE PROBLEMS

Figure 1, the local area map showing the LOP's (lanes for simultaneous pairs in the southeastern Ohio region), illustrated some of the problems of lane geometry and relative precision applied to typical OMEGA use situations. All of the possible station pair combinations of potential interest to users in an area at least the size of the state of Ohio are tabulated in Figure 24. Here the relative tilts of the parallelograms formed by the lane pair intersections and the aspect ratios of the lane widths are listed. It will be observed that in no case are these lane distances like the often quoted 8 miles on the baseline, and in some cases a lane three times longer between crossings is observed. This is the case for the C-D pair where Ohio is located around the bend of the hyperbolic isophase contours or on the far side from both stations.

A figure of merit indicating the quality of the grid from a geometric standpoint is easily computed combining the smallest angular tilt with the aspect ratio. A figure of merit of 1 would be a best choice if possible. In practice, the A station is not usable in Ohio many times, or is very noisy because of the Greenland ice cap shadowing of the reception zone and consequent high signal attenuation. Of the remaining combinations of grid pairs, the simultaneous pairs B-C and C-D are the best choice at a relatively low figure of merit. This is a usable combination in Ohio as long as the user keeps in mind the relatively long spacing of 28 miles between the C-D LOP's.

The problem for simplified OMEGA is to provide the user with some kind of easily used software. A possible approach to this problem might be simplified charts compressing roughly four times the area of Figure 1, only computed based on rectangular OMEGA grids

with appropriate compass directions and non-linear distance scales. A book of small charts for major areas of the world would provide the navigator with a quick navigation aid for use with the readout system suggested here. The preparation of this software on large scale computers should be easily possible and would save the small receiver user the cost of the all electronic computation methods applied in the present sophisticated OMEGA processors. Similar software applied to diurnal corrections might take the form of course overlays for selected areas. If the end use of the OMEGA system is thought of in a relative way rather than as an absolute position determination device, these course charting aids in rectangular OMEGA coordinates might reduce the present complexity by nearly an order of magnitude.

(Note added in review)

An example of a rectangular OMEGA grid is illustrated in Figure 29 for 3.4 KHz difference frequency lanes in the Boston-Cape Cod area. The map covers an area of roughly 5000 square miles. The elliptical compass rose of the rectangular grid could be calibrated such that any diameter would represent a relative distance on the map, as for example the inner diameter of Figure 29 is approximately one 10.2 KHz lane or about 8 miles.

## EXPERIMENTAL RESULTS AND THE FUTURE

Figure 25 is a photograph of a breadboard bench processor in which most of the concepts described in this report have been evaluated. As of this writing the Hawaii C channel is still off the air for repairs and Norway provides only marginal use signals in Ohio; thus, direct measurement of simultaneous pairs has not been thoroughly evaluated. However, in December of 1973 when Norway began operating again, a few measurements were made using the 40.8 processors described but with a front end filter bandwidth of 35 Hz. The results are shown in Figure 26. The Norway signal level is seldom good enough in Ohio to provide pair information even for commercial receivers. However in this case the receiver appeared to be trying to track the signal phase. One bit increment on this recording represents about 1/8th of a mile at the 40.8 KHz frequency used. Also illustrated in Figure 26 is the case where no signal is present in the C channel when attempting to measure a B-C simultaneous pair. The phase difference averages out to halfway between a lane transition or a count of 8 and simply does not move because the B signal is being compared to a C signal with random phase, or just noise.

Figure 28 illustrates the magnitude of the sunrise transient at North Dakota with respect to Ohio. Here an external atomic clock and synthesizer were used to generate a stable 13.6 KHz signal to compare with the D channel on 10.2 KHz. One bit of the data of Figure 28 would represent about 1/4th of a mile in this direct ranging comparison with a local clock. The resulting 40.8 KHz lane shifts 2 transitions or about 8 miles over a period of 30 minutes, but is reasonably stable before and after the transition.

Some one-way ranging experiments have been made on the D channel using an

external oscillator offset to show a rapid simulated lane change rate. The external oscillator was relatively noisy compared to a crystal reference and roughly simulates comparing two relative strong signals of 10 db s/n or better. A recording of the result is shown in Figure 27 comparing the D channel with the external oscillator. This illustrates the effect of motion and phase detection at general aviation aircraft velocity for the 40.8 KHz lane transitions. Presently signals are being received on a breadboard system in a continual state of developmental change of the processing details. A brass-board airborne model is in the design state and a project on the mechanical-optical details of the OMEGA NAVMAP system is underway.

A breadboard system for a 10.2 KHz processor which uses some of the 40.8 methods with an up-down counter has been devised. Some longer range plans of the program include the investigation of simplified methods of using loop antennas, noise cancelling antenna systems for aircraft, system studies of the software data reduction problem, 4 bit binary processors for OMEGA map conversions, and a 3.4 KHz difference frequency processor for long range navigation use.

The results of this project to date indeed indicate that low cost OMEGA with less complexity than a color TV set is an excellent possibility if proper respect for the basic idea of binary simplicity is shown. It is quite fortunate that Professor Pierce of Harvard, the system inventor, thought of the system in simple integer relations which make direct binary processing and display possible with minimal decimal conversions required.

## ACKNOWLEDGEMENTS

This project has been supported by NASA Langley Research Center Grant NGR 36-009-017 for application of low cost methods to provide OMEGA-VLF navigation aids for the general aviation pilot. The direction of Professor Richard H. McFarland, Professor G. E. Smith; and the help of student interns, John Abel, Harry Graham, Kent Chamberlin, Rich Salter, Dan Ellis, and Dan Moyer is greatly appreciated on the results of this project.

## REFERENCES

The major references of interest are:

J. A. Pierce, "OMEGA: A Worldwide Navigational System, System Specifications and Implementation", NTIS, U. S. Department of Commerce, No. AD 630-900, May 1, 1966.

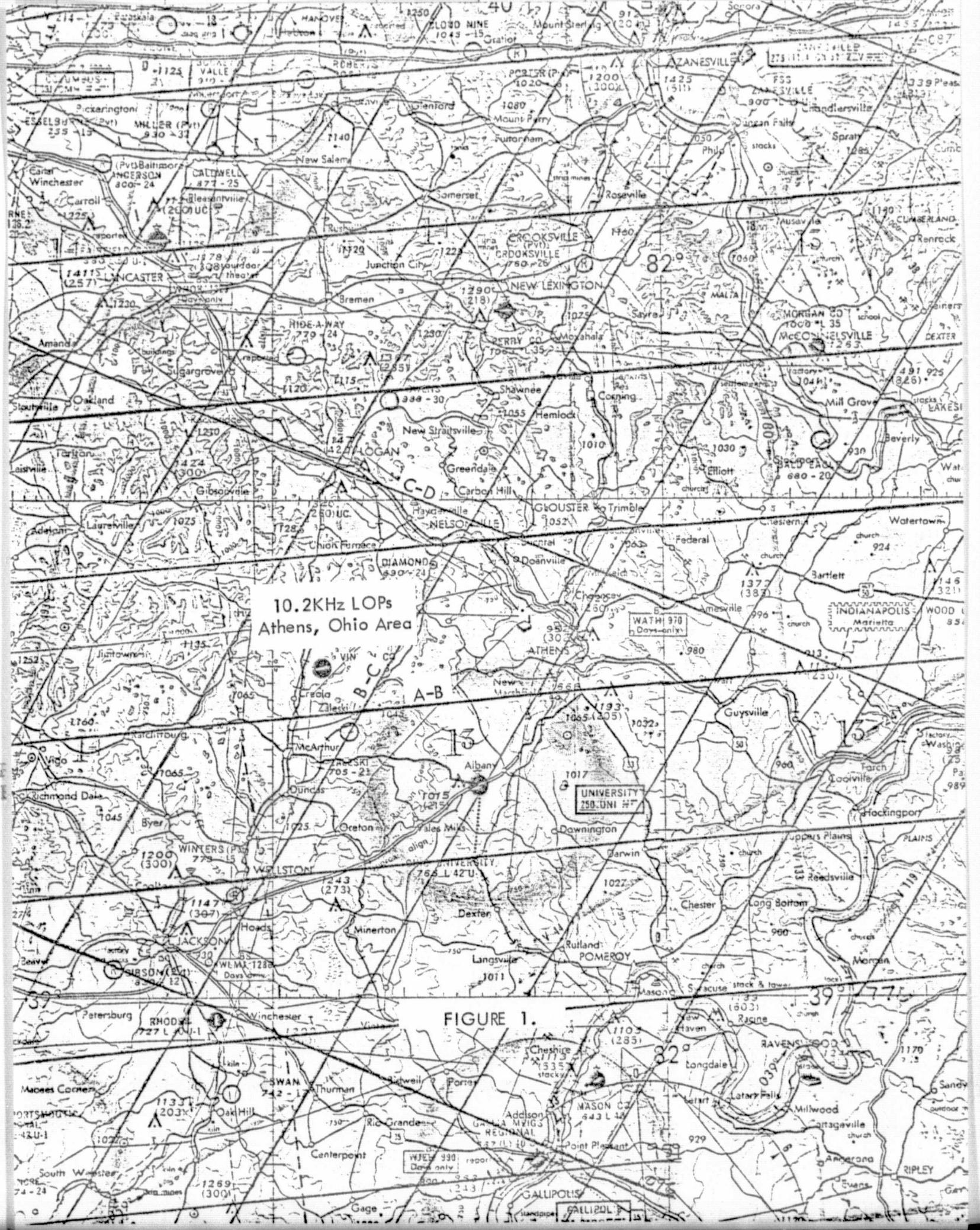
"Proceedings of the First OMEGA Symposium", Institute of Navigation, Washington, D. C., November 9-11, 1971

There are about 30 references on OMEGA in the "Journal of the Institute of Navigation" published in 1968-1973.

SIMPLIFIED OMEGA RECEIVERS

**FIGURES 1 through 29**

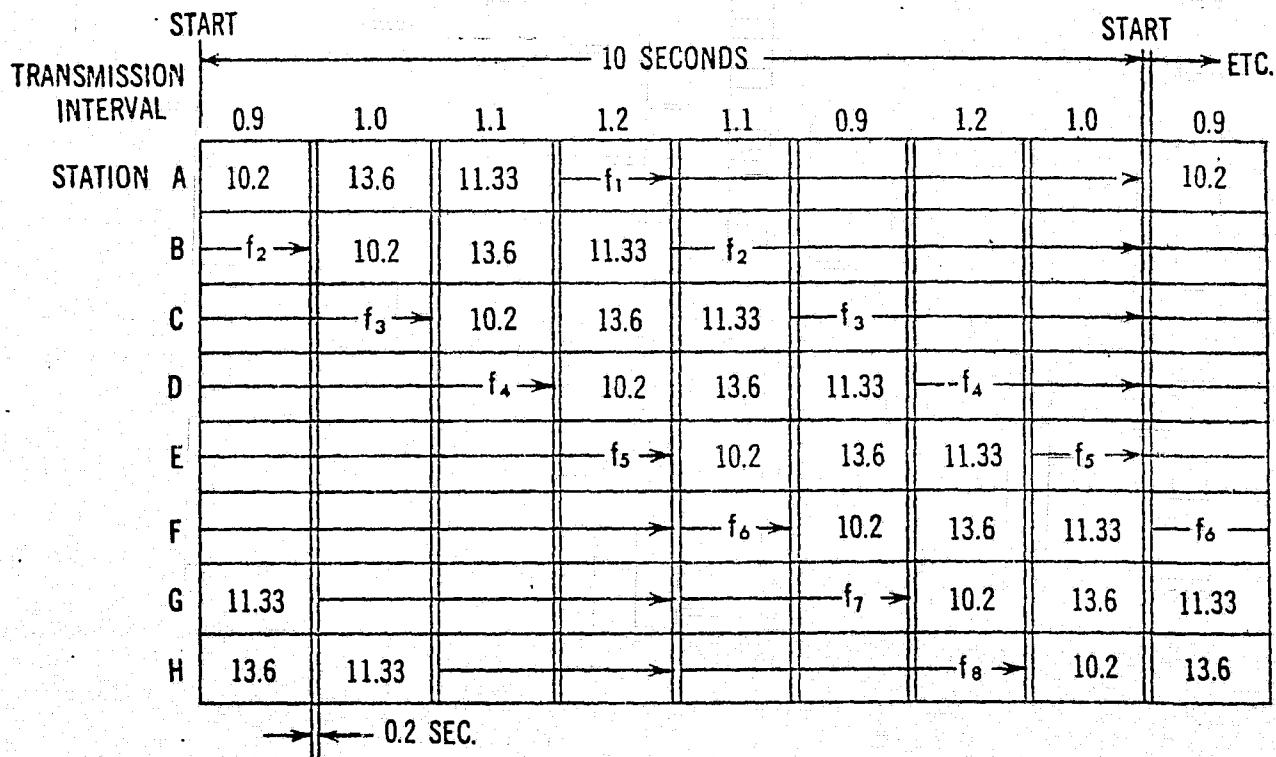
**PRECEDING PAGE BLANK NOT FILMED**



### OMEGA Stations

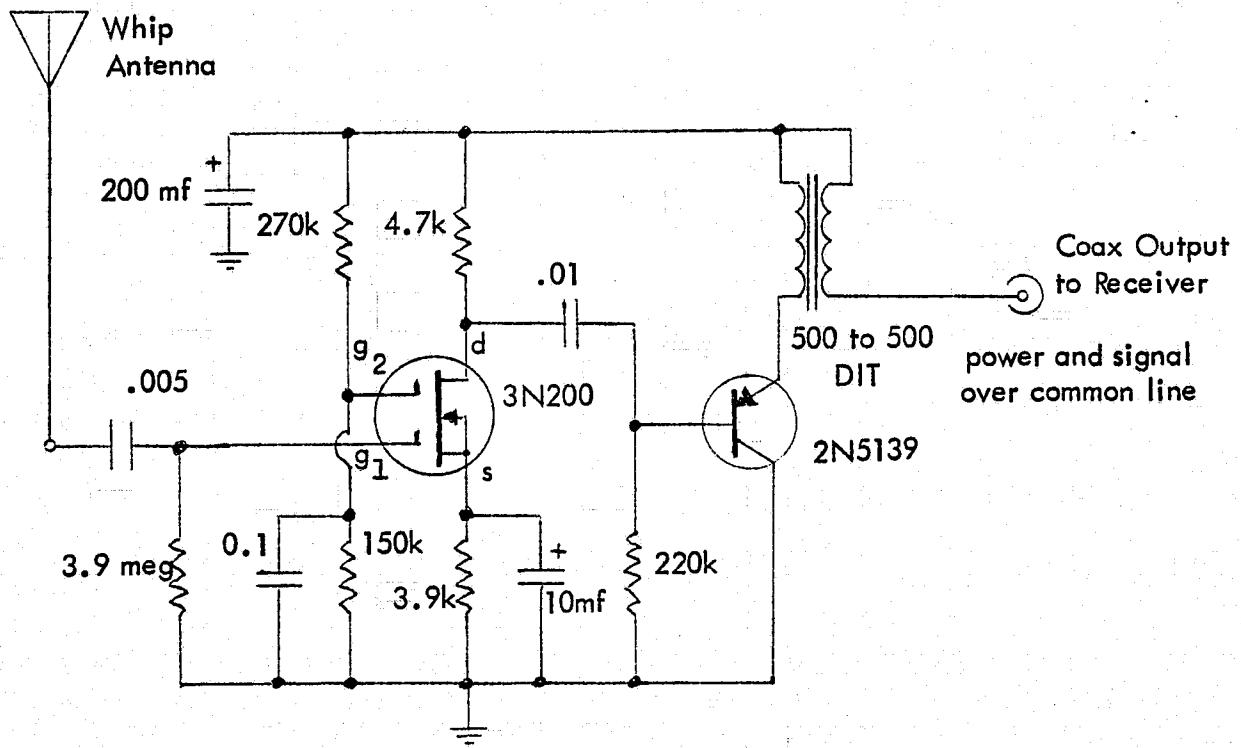
Station Name	Designator	Latitude	Longitude
Norway	A	66°25'15.00"N	18°09'10.00"E
Trinidad	B	10°42'06.20"N	61°38'20.30"W
Hawaii, U.S.A.	C	21°24'16.90"N	157°49'52.70"W
North Dakota, U.S.A.	D	46°21'57.20"N	98°20'08.77"W
Reunion	E	20°58'26.47"S	55°17'24.25"E
Argentina	F	43°03'12.53"S	65°11'27.69"W
Australia	G		
Japan	H	34°36'53.26"N	129°27'12.49"E

These stations will provide coverage over the entire surface of the earth with a theoretical probable error of positioning of  $\pm$  one to  $\pm$  two nautical miles. Signals from stations can be received out to maximum usable ranges of 5000 n mi. to 7000 n mi. from the transmitters depending on the bearing of the receiver from the transmitter. The shorter range can be expected at reception points west of stations located near the magnetic equator. Signals are also severely attenuated whenever a propagation path falls across land which is overlaid with a thick ice sheet. Reception in the Greenland and Antarctica shadow zones will be effectively blocked.



OMEGA SIGNAL FORMAT

FIGURE 2

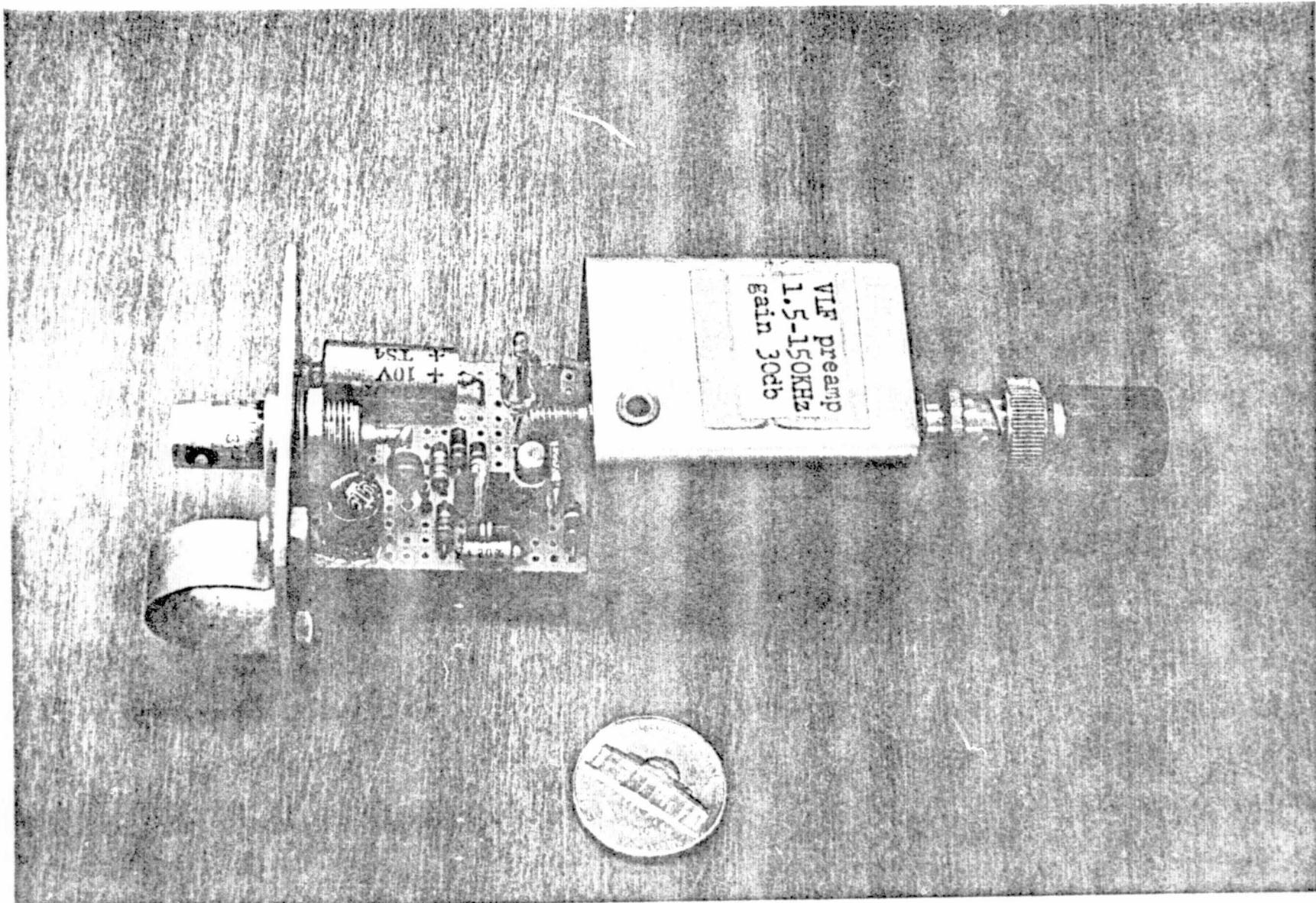


WIDE BAND PREAMPLIFIER

(10db gain, 1.5 - 150 KHz)

FIGURE 3

ORIGINAL PAGE IS  
OF POOR QUALITY



PHOTOGRAPH OF VLF PREAMPLIFIER ASSEMBLY

FIGURE 4

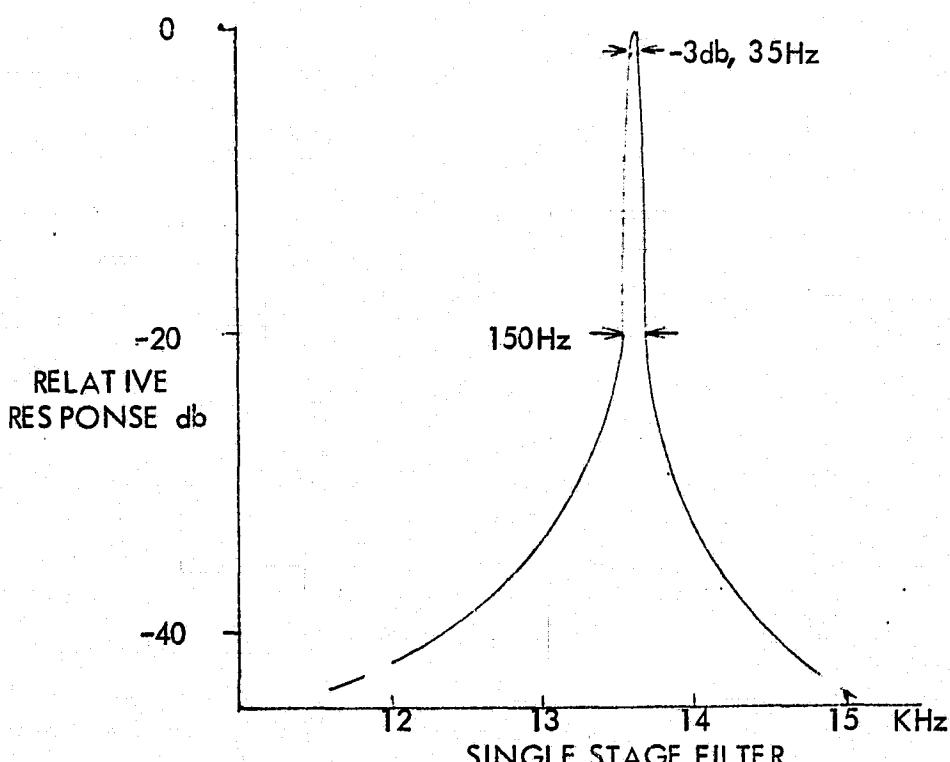


FIGURE 5

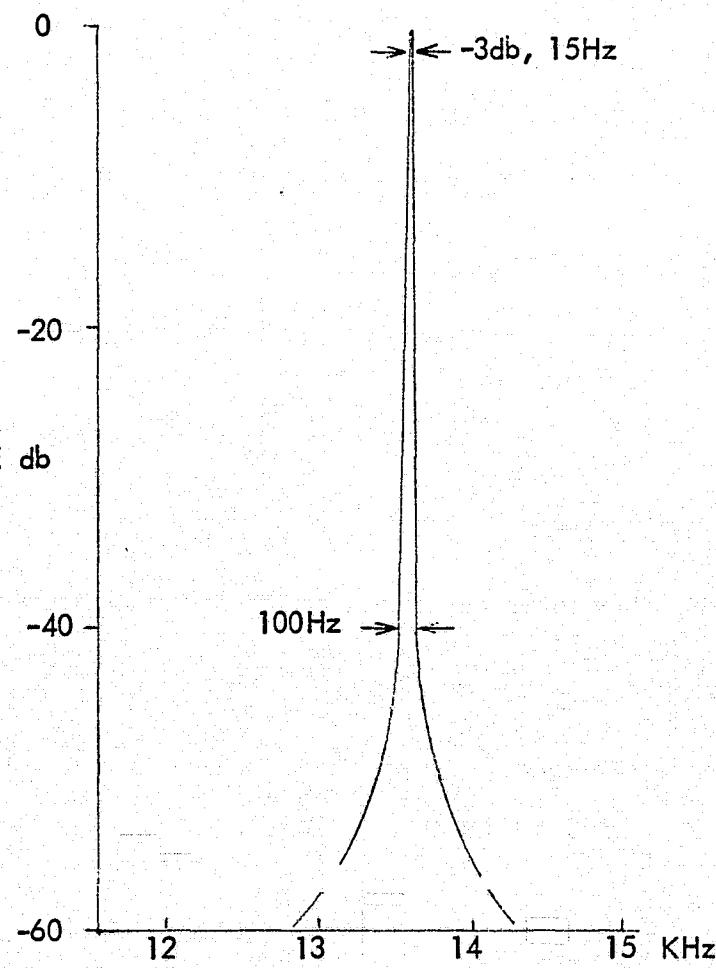
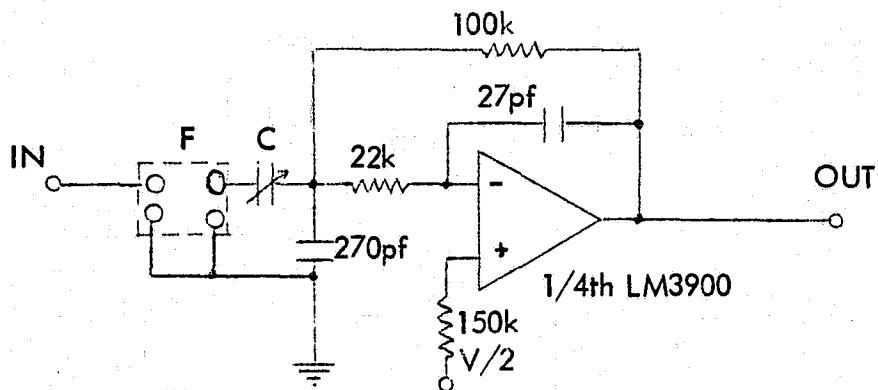


FIGURE 7

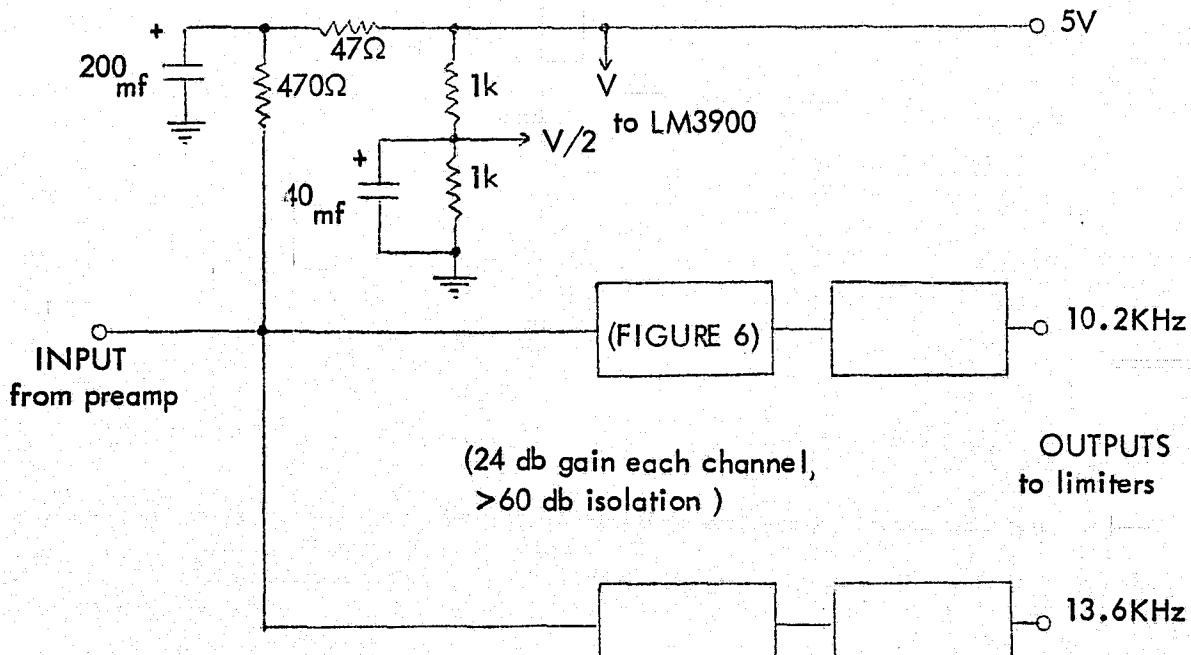


F Vernitron ceramic filter  
LF-10.2B  
LF-13.6B

C Tuning capacitor  
 $\sim 220\text{pf}$  at 10.2KHz  
 $\sim 120\text{pf}$  at 13.6KHz

### SINGLE STAGE FILTER BLOCK

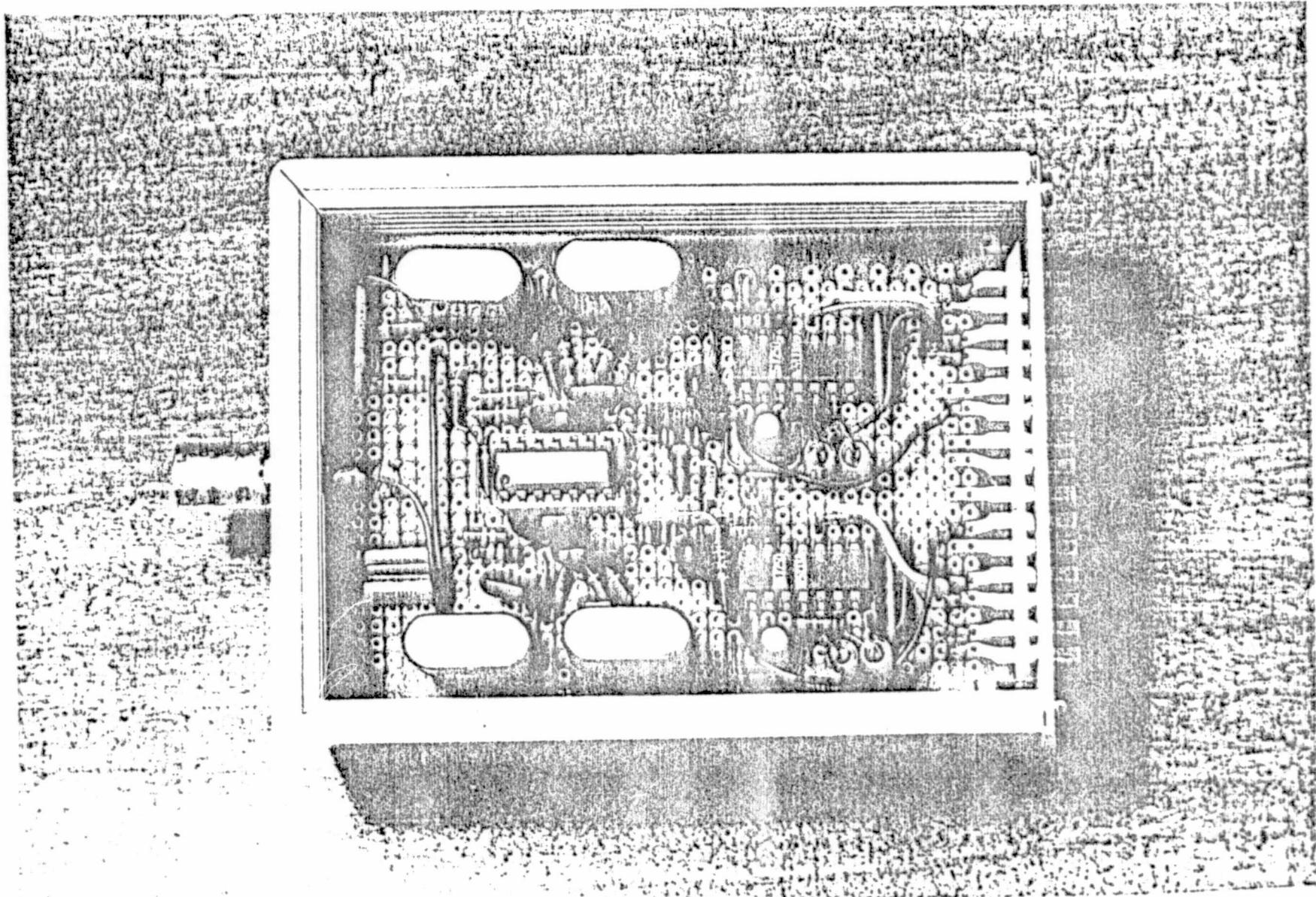
FIGURE 6



TWO STAGE , TWO CHANNEL FILTER

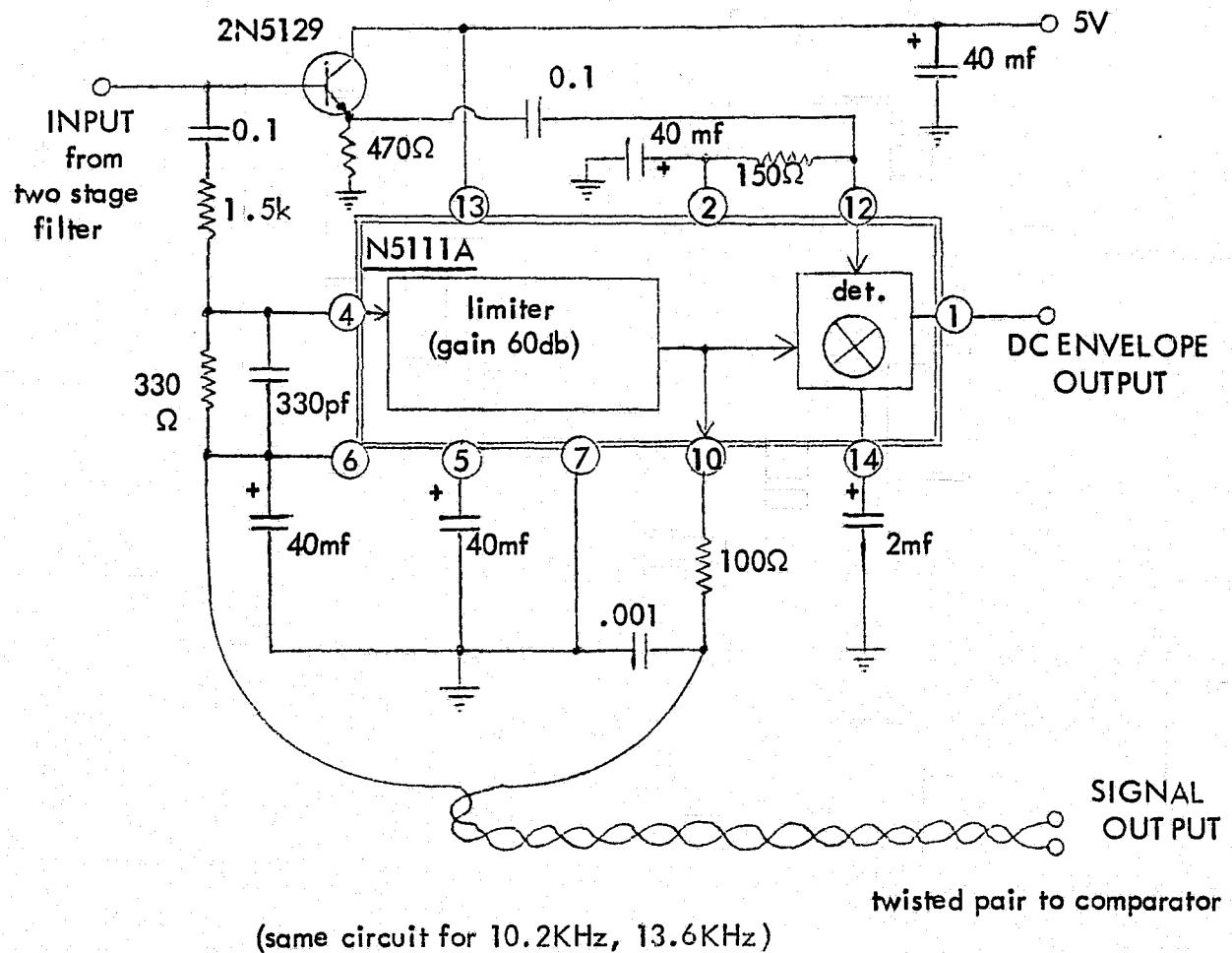
FIGURE 8

ORIGINAL PAGE IS  
OF POOR QUALITY



PHOTOGRAPH OF TWO CHANNEL FILTER-LIMITER ASSEMBLY

FIGURE 9



(same circuit for 10.2KHz, 13.6KHz)

### LIMITER - ENVELOPE DETECTOR

FIGURE 10

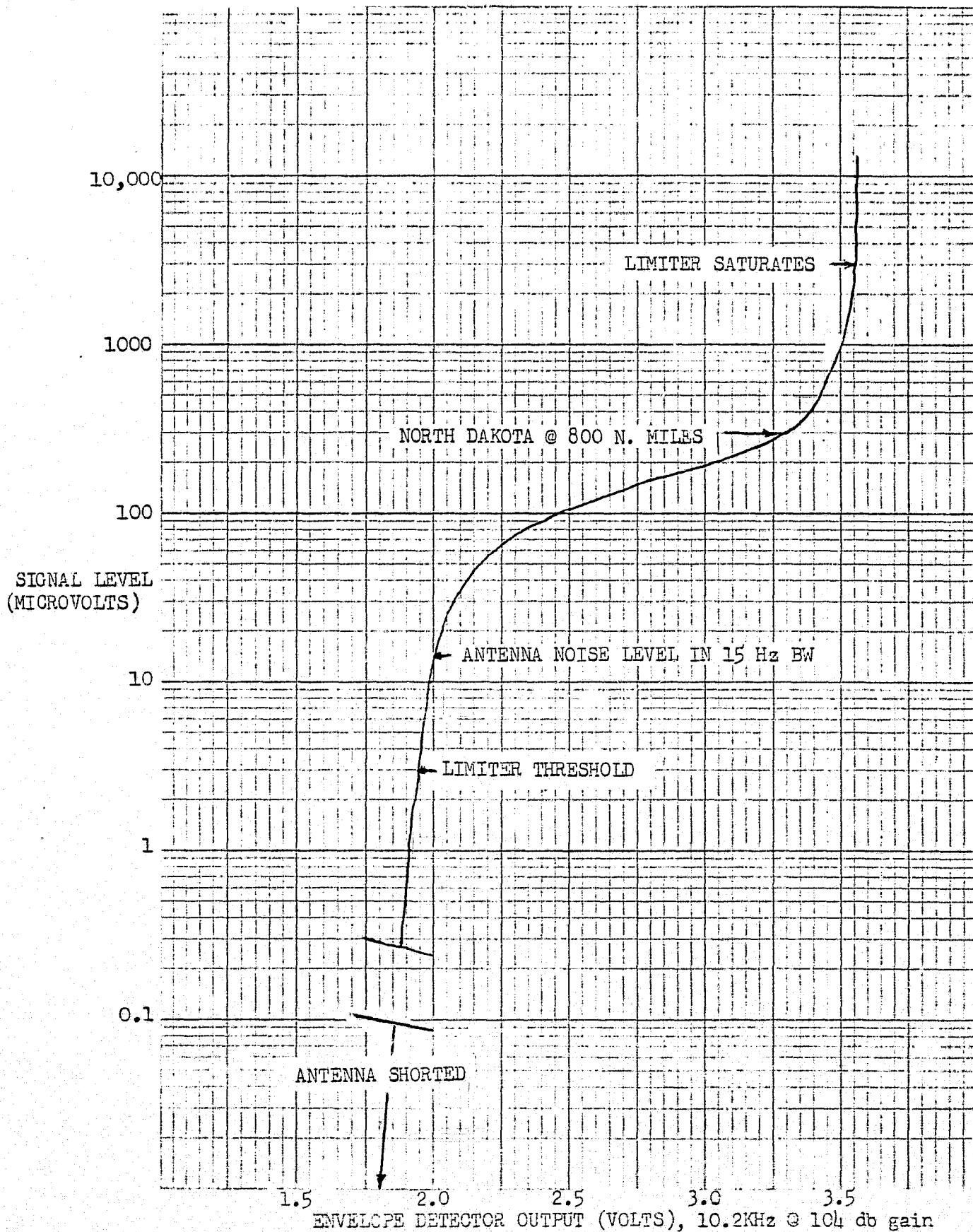
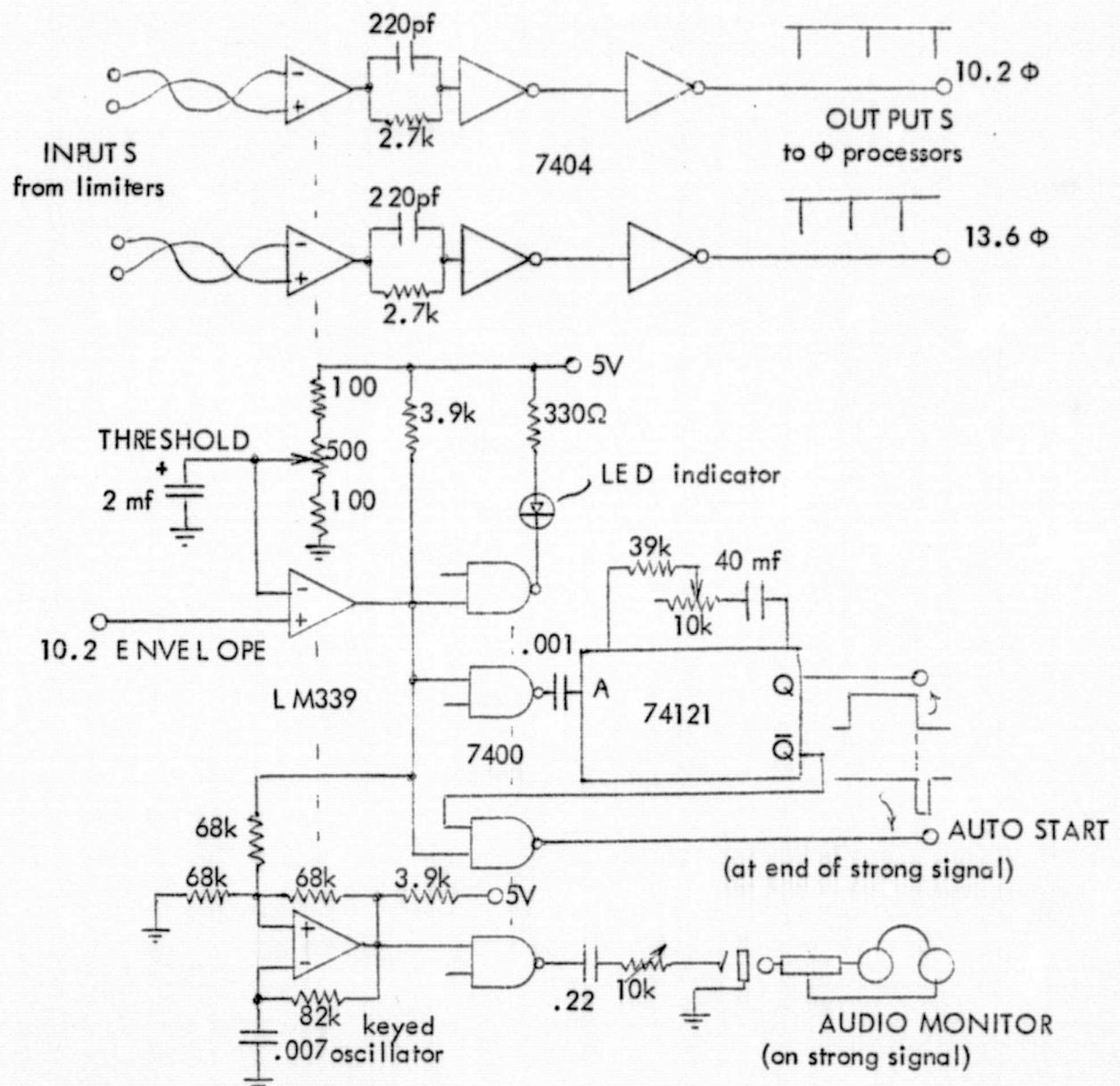
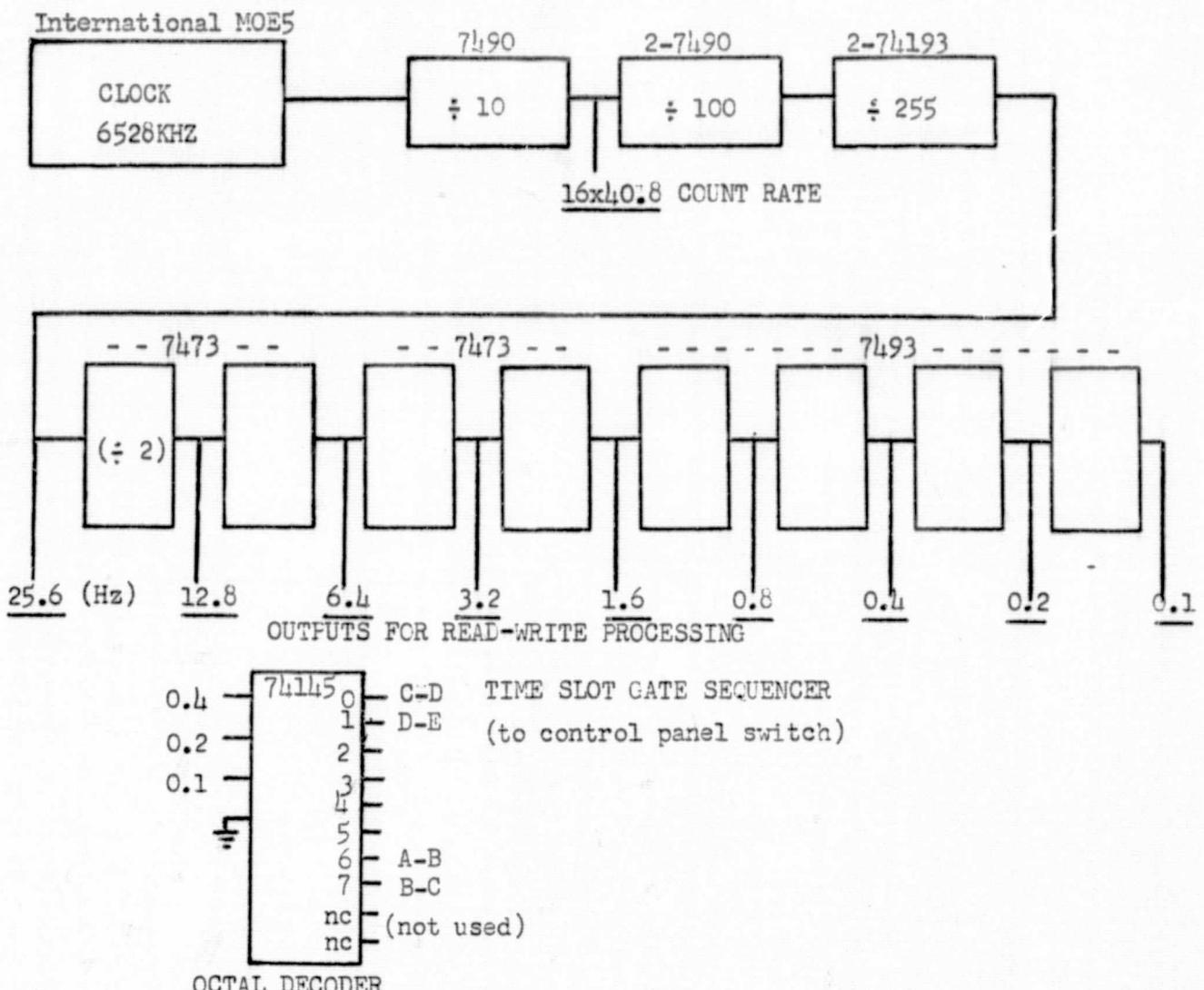


FIGURE 11



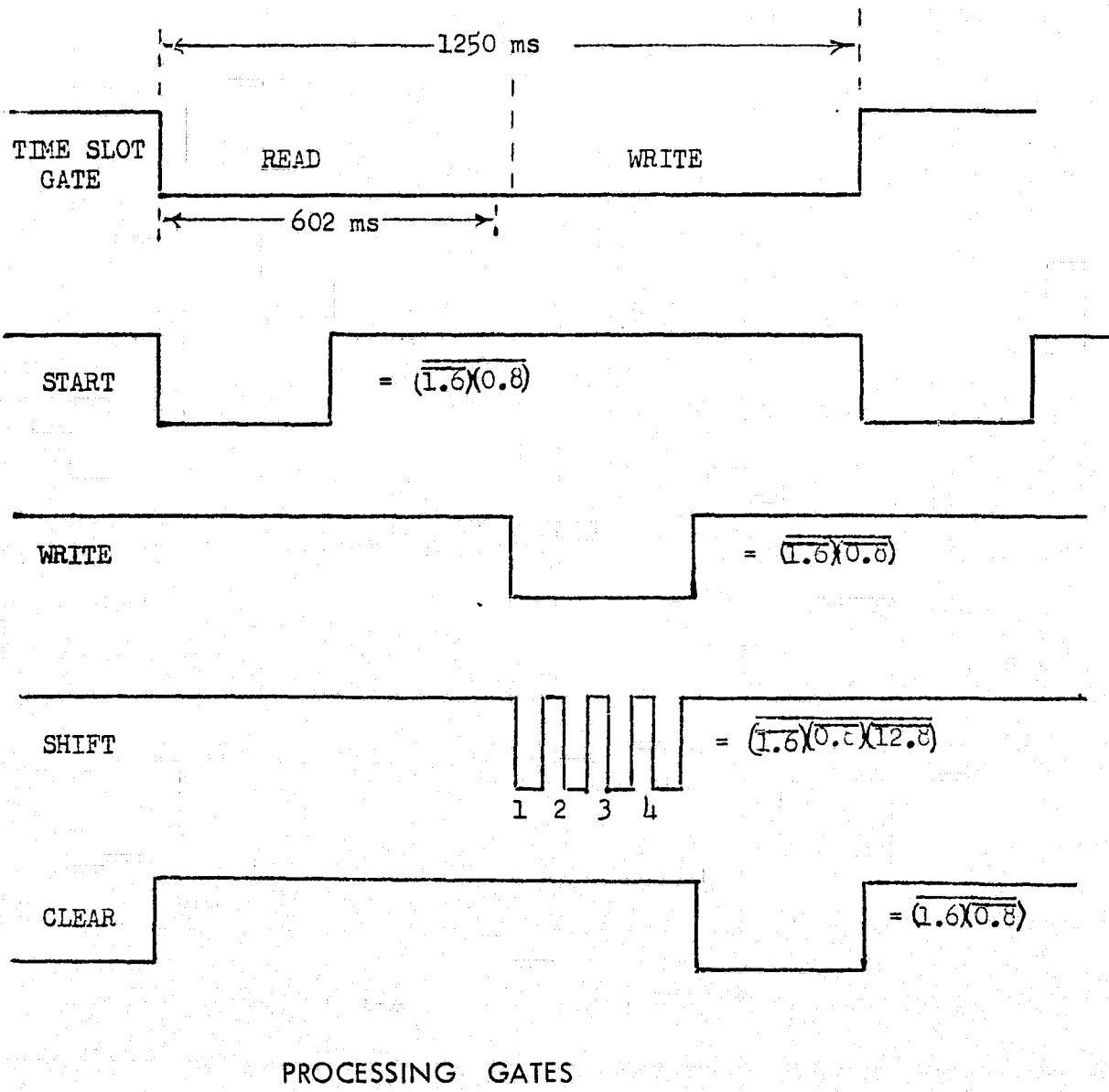
ZERO CROSSING DETECTORS and STRONG SIGNAL MONITOR

FIGURE 12



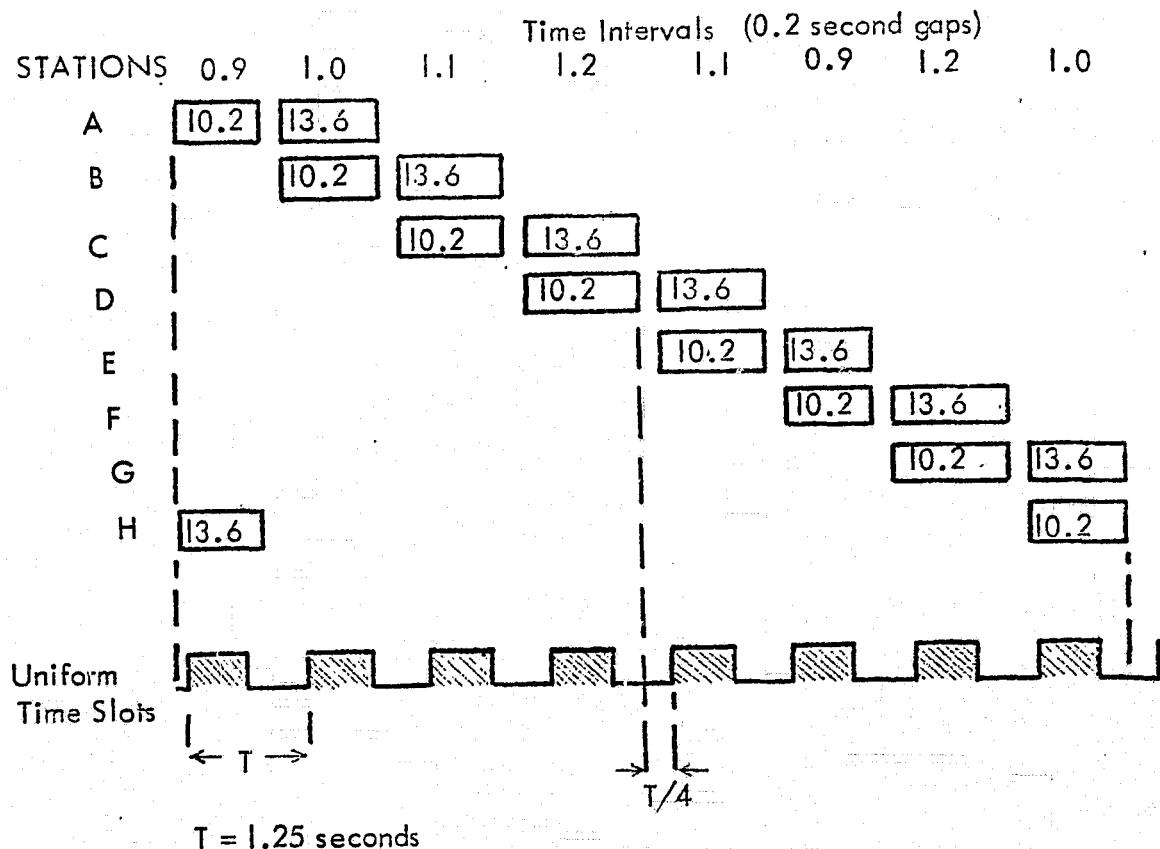
H K T CIRCUITS

FIGURE 13



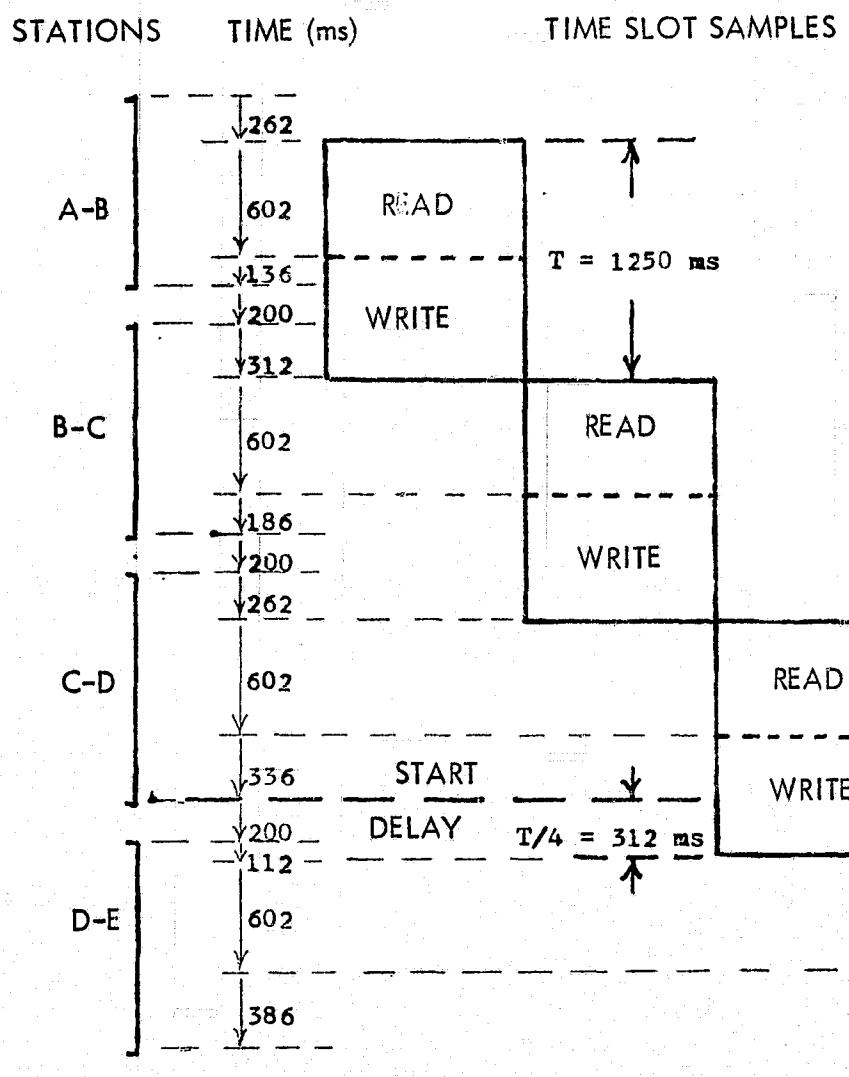
### PROCESSING GATES

FIGURE 14



SIMULTANEOUS PAIR OMEGA SIGNAL FORMAT

FIGURE 15



UNIFORM TIME SLOT SAMPLING OF OMEGA PAIRS

FIGURE 16

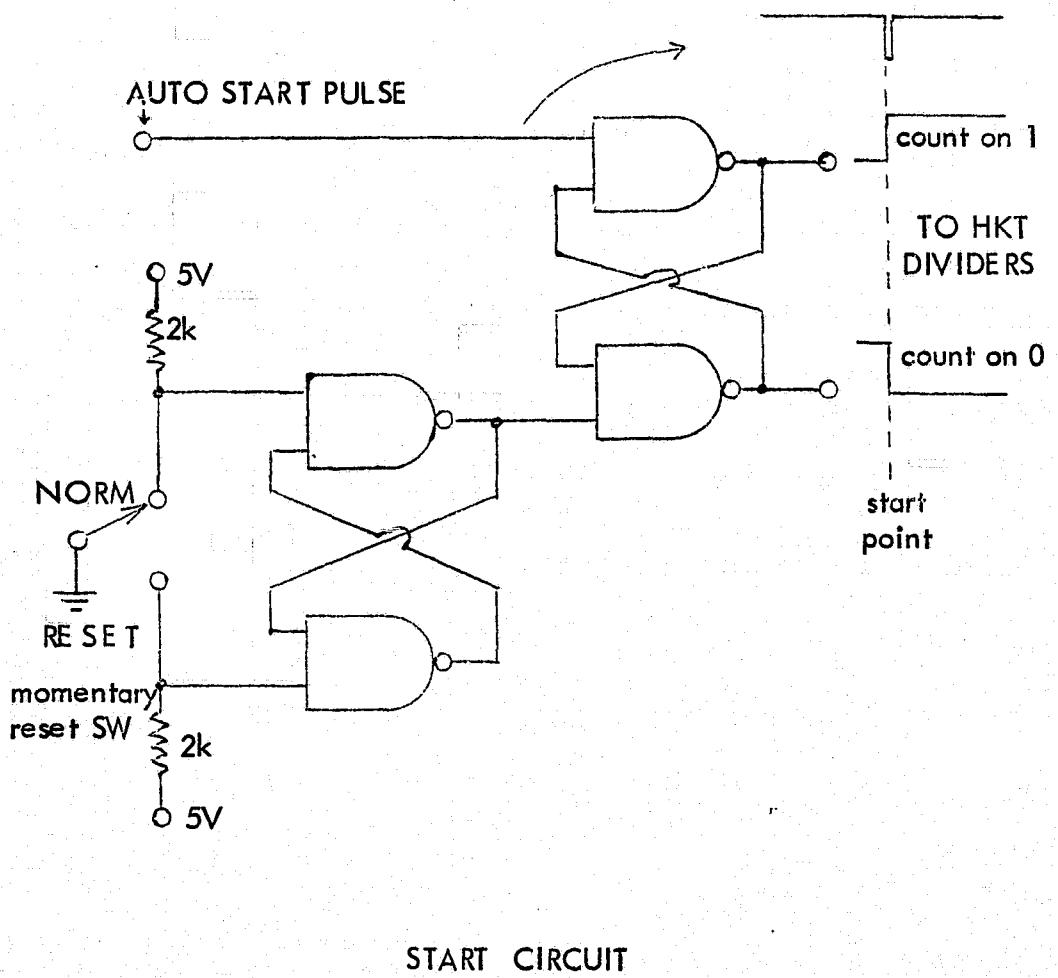


FIGURE 17

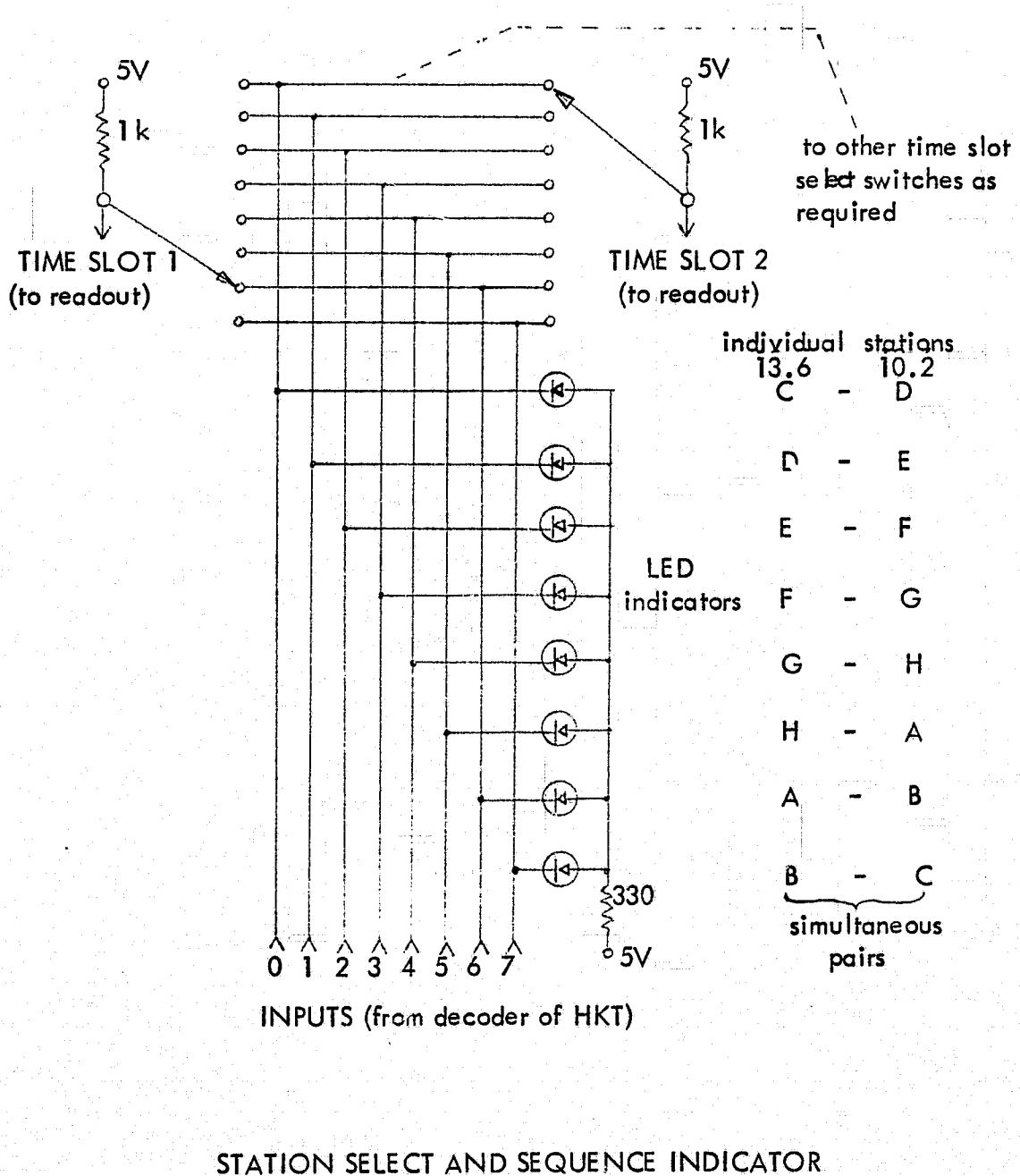


FIGURE 18

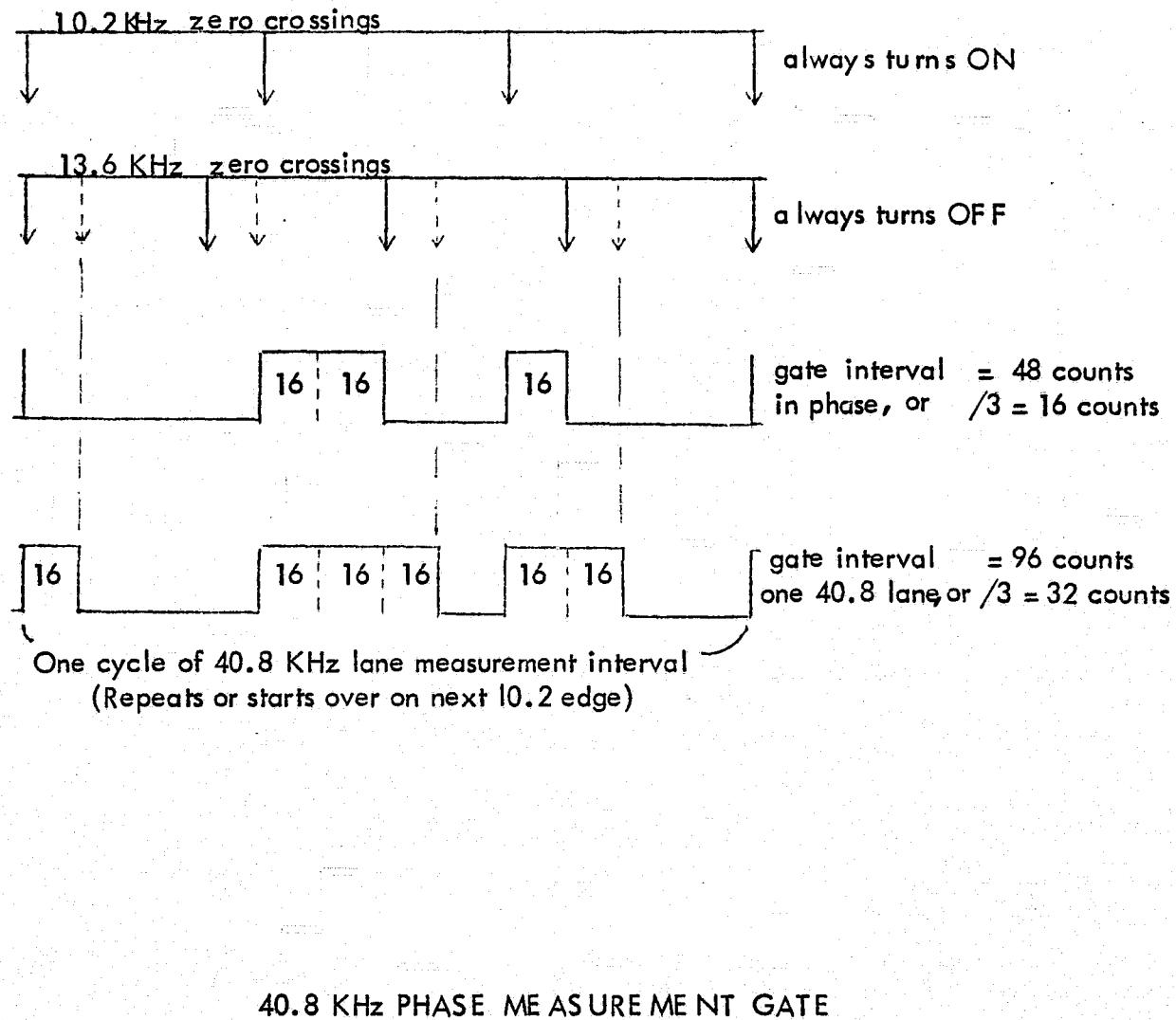
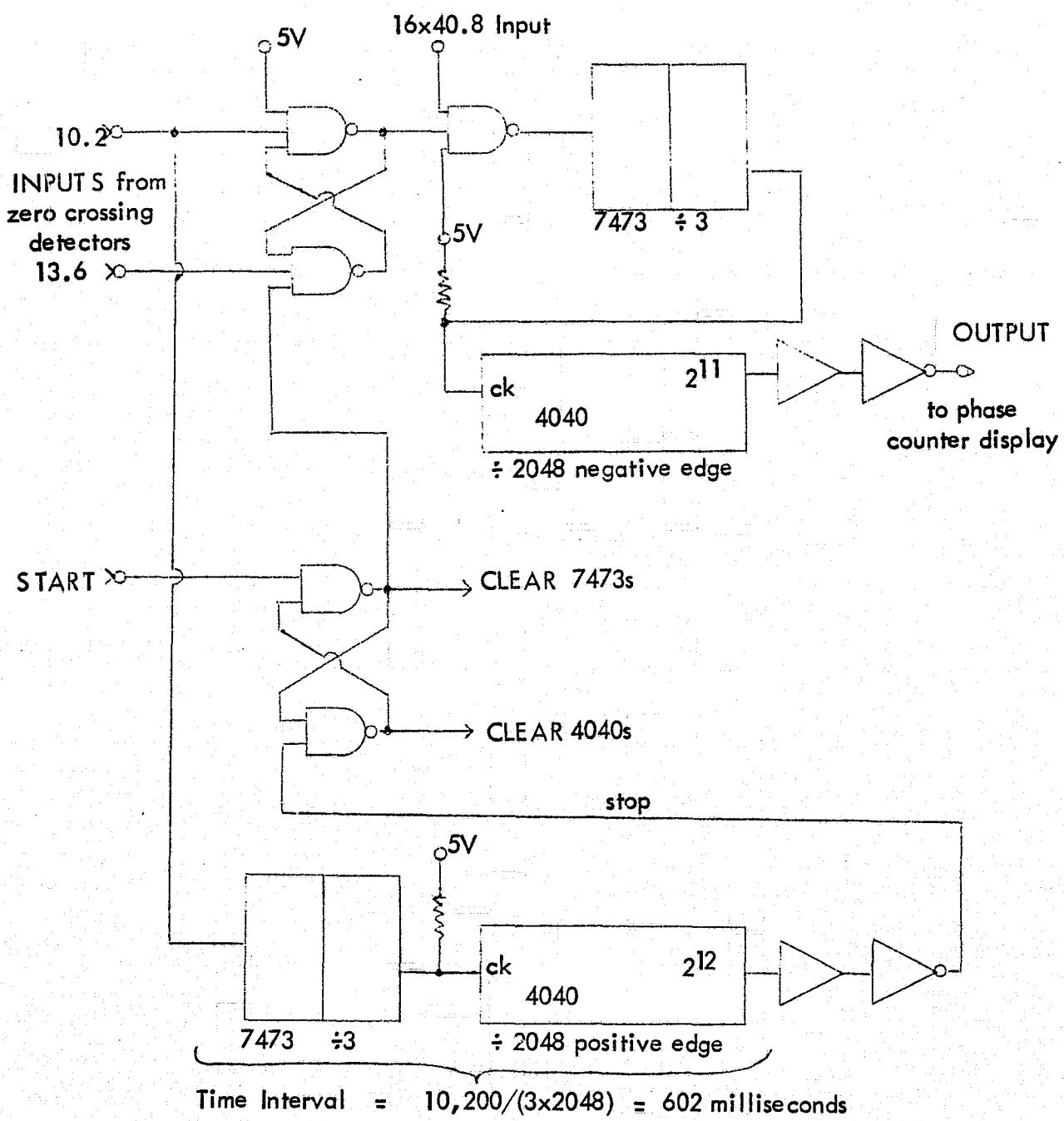
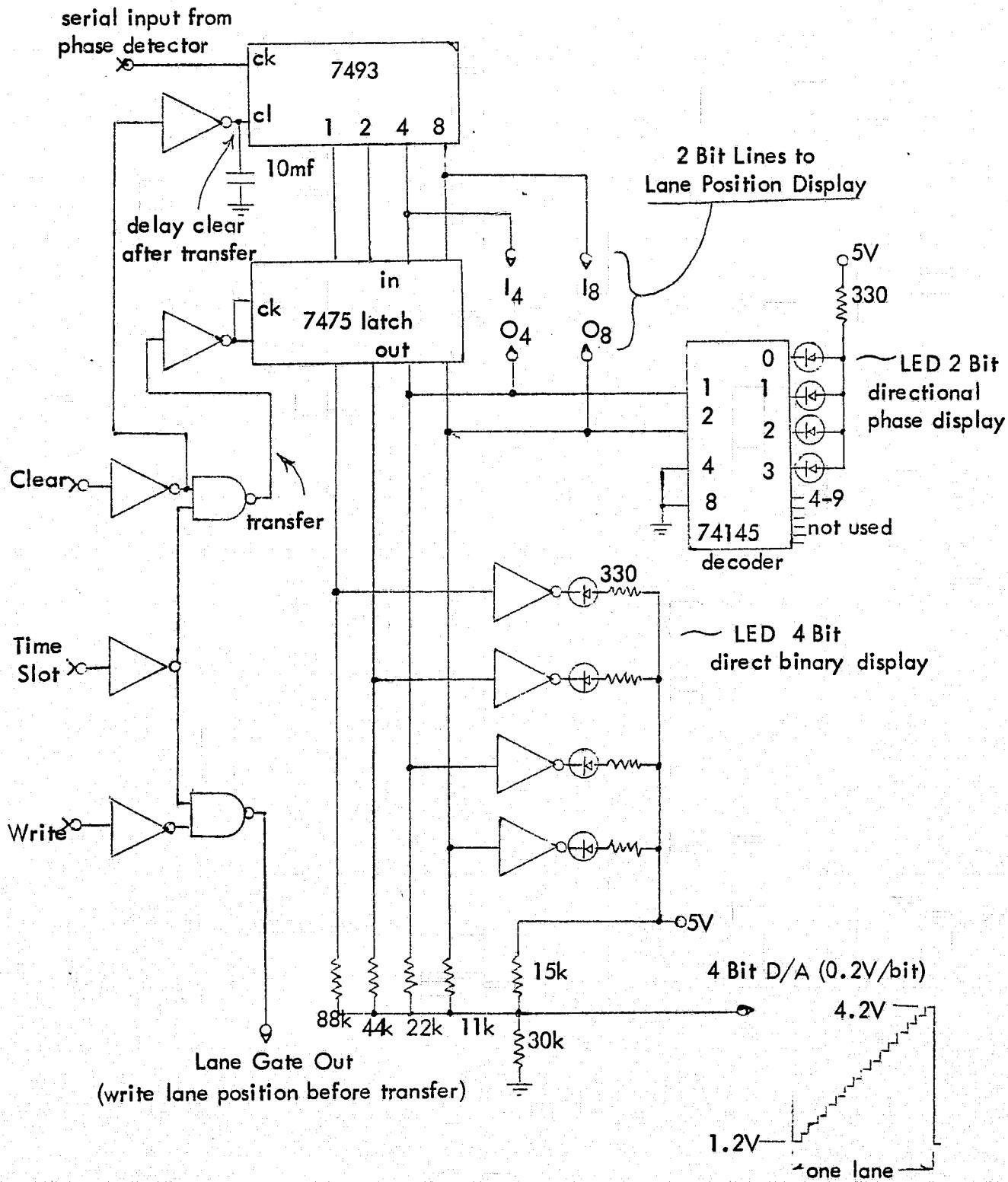


FIGURE 19

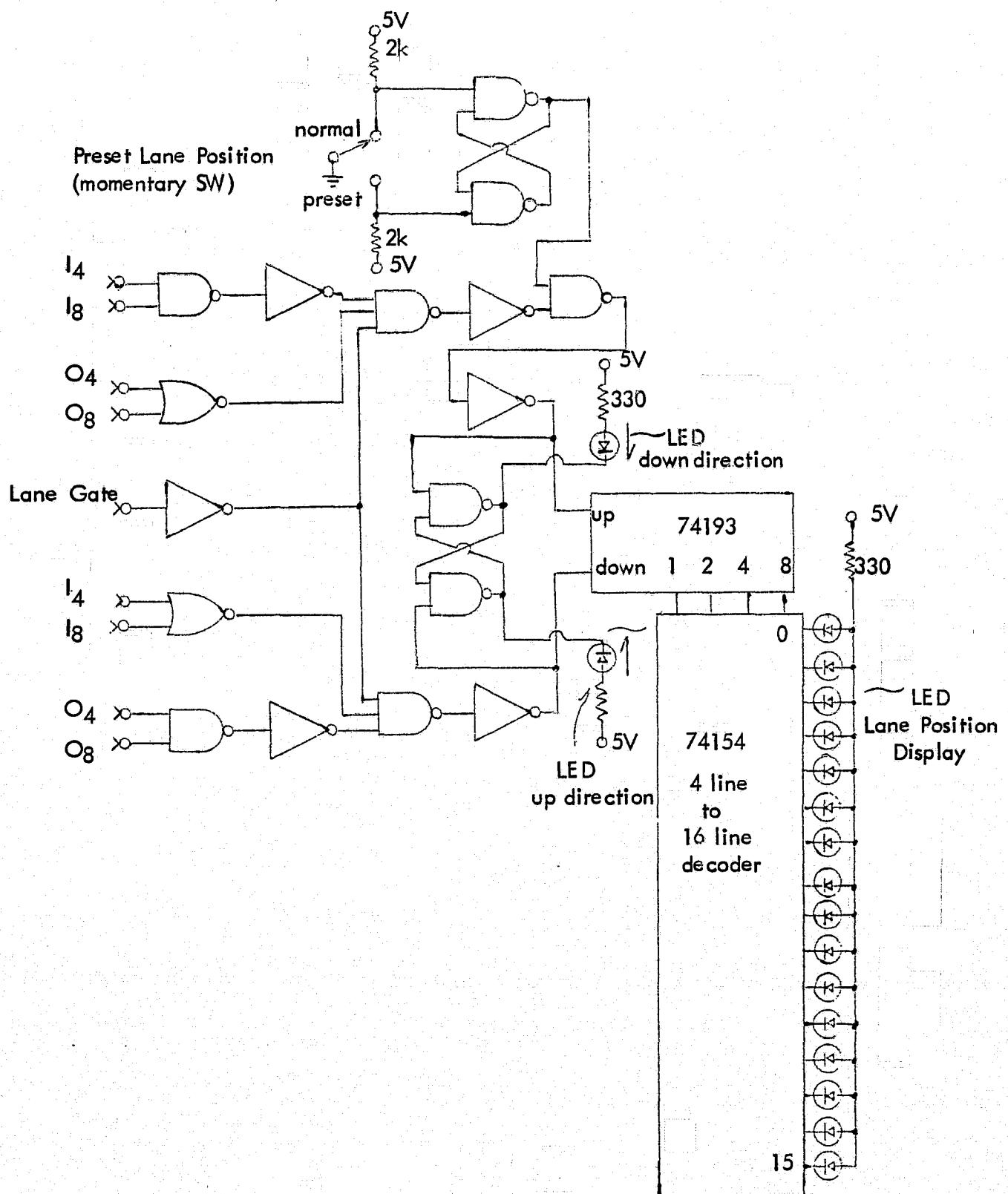


SIMULTANEOUS PAIR PHASE DETECTOR-DIVIDER

FIGURE 20



## ALTERNATIVE DISPLAYS FOR PHASE COUNTER

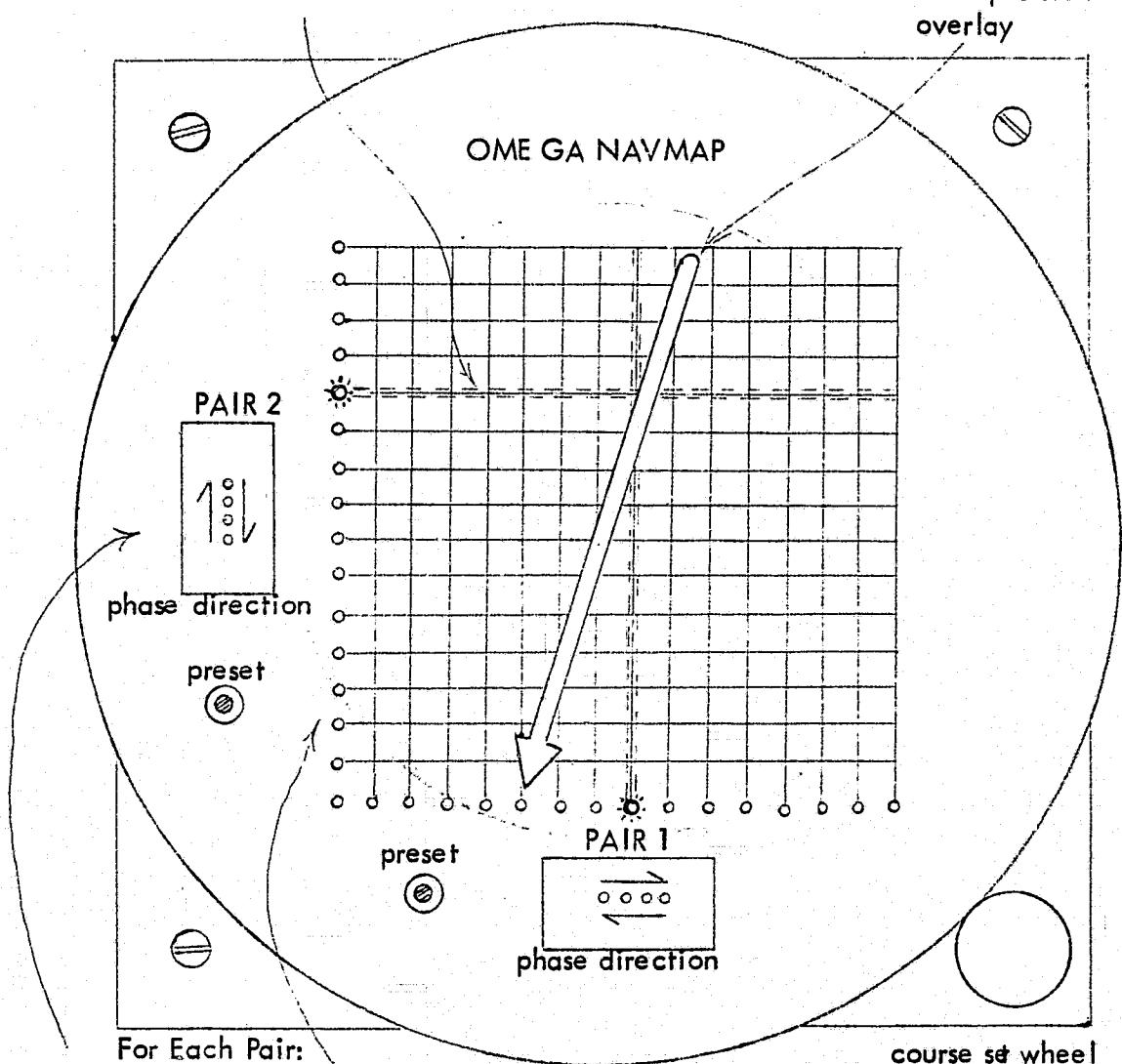


LANE POSITION and DIRECTION DISPLAY

FIGURE 22

EDGE LIGHTED LINES

course position  
overlay



For Each Pair:

2 bit phase count data (decoded)      4 bit lane count data (decoded)

PROPOSED OMEGA LANE MAP DISPLAY

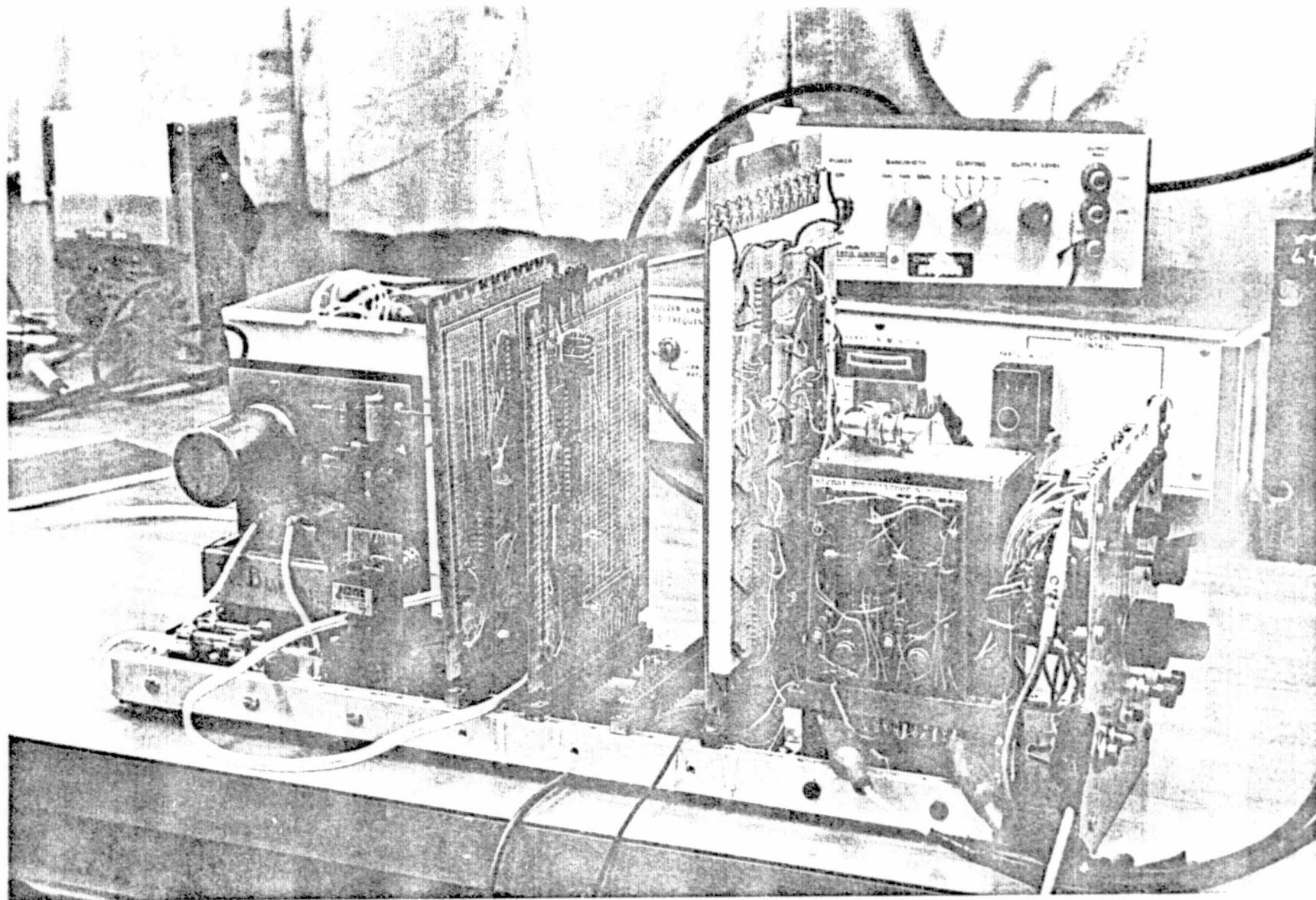
FIGURE 23

LANE PAIRS	ADJACENT ANGLES ( $\alpha$ )	TIET SINE $\alpha$	LANE WIDTHS (N. MILES)	=	ASPECT RATIO (A)	MERIT A SIN $\alpha$
A-B; A-C	67° - 113°	.92	9.6/9.9	=	.97	.875
A-B; A-D	81° - 99°	.98	9.6/11.7	=	.82	.80
A-B; B-D	42° - 138°	.69	8.5/9.6	=	.89	.61
B-C; A-C	58° - 122°	.85	9.0/9.9	=	.91	.77
B-C; A-D	44° - 136°	.69	9.0/11.7	=	.77	.53
B-C; B-D	12° - 168°	.21	8.5/9.0	=	.94	.20
C-D; A-C	41° - 139°	.65	9.9/28.3	=	.35	.23
C-D; A-D	54° - 126°	.81	11.7/28.3	=	.41	.33
C-D; B-D	68° - 112°	.92	8.5/28.3	=	.30	.28
A-C; A-D	12° - 168°	.21	9.9/11.7	=	.85	.18
A-C; B-D	71° - 109°	.94	8.5/9.9	=	.86	.81
A-D; B-D	57° - 123°	.84	8.5/11.7	=	.73	.61
A-B; B-C	55° - 125°	.82	9.0/9.6	=	.94	.77
B-C; C-D	82° - 98°	.99	9.0/28.3	=	.32	.32
A-B; C-D	27° - 153°	.45	9.6/28.3	=	.34	.15

OMEGA GRID FIGURE OF MERIT  
(FOR ATHENS, OHIO AREA)

FIGURE 24

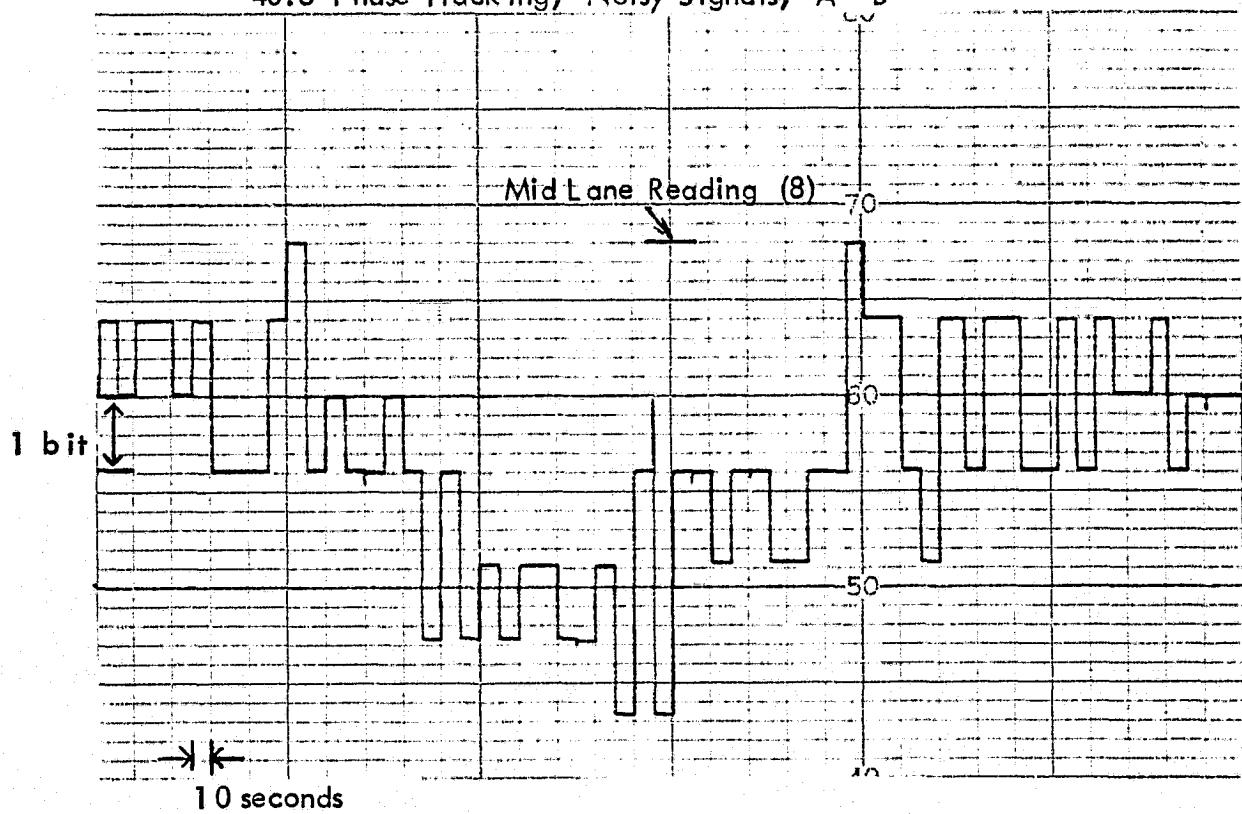
ORIGINAL PAGE IS  
OF POOR QUALITY



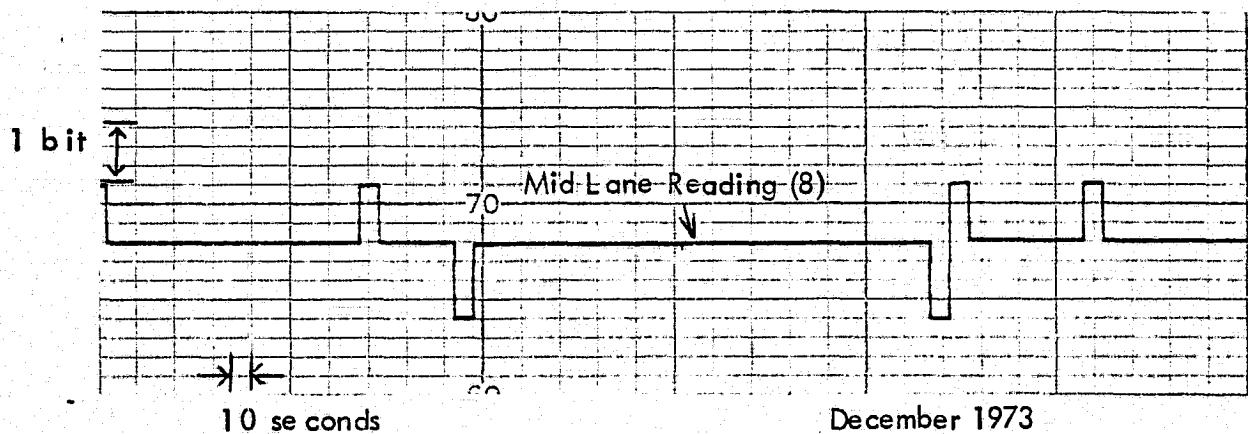
PHOTOGRAPH OF EXPERIMENTAL BENCH PROCESSOR

FIGURE 25

40.8 Phase Tracking, Noisy Signals, A - B



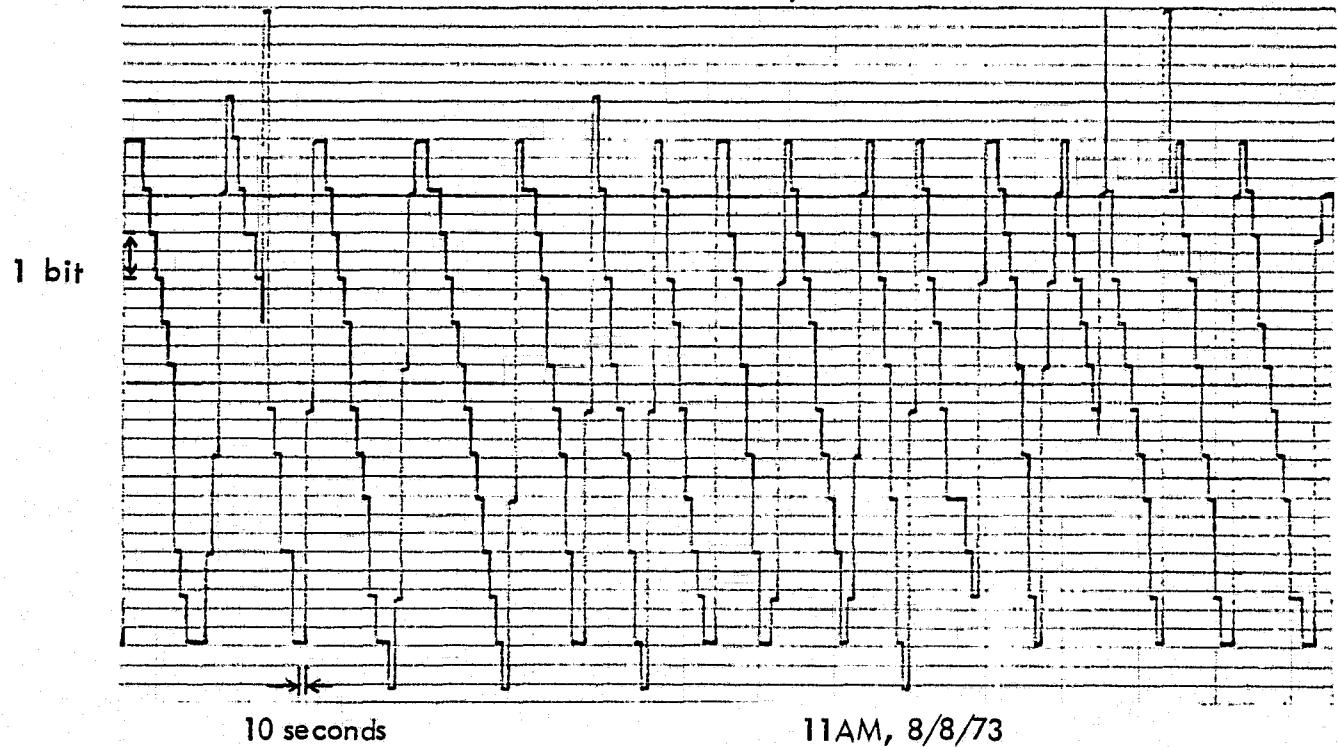
40.8 Phase Tracking, No Signals on C, (Hawaii shut down) B - C



40.8 KHz Phase Detector D/A Output

FIGURE 26

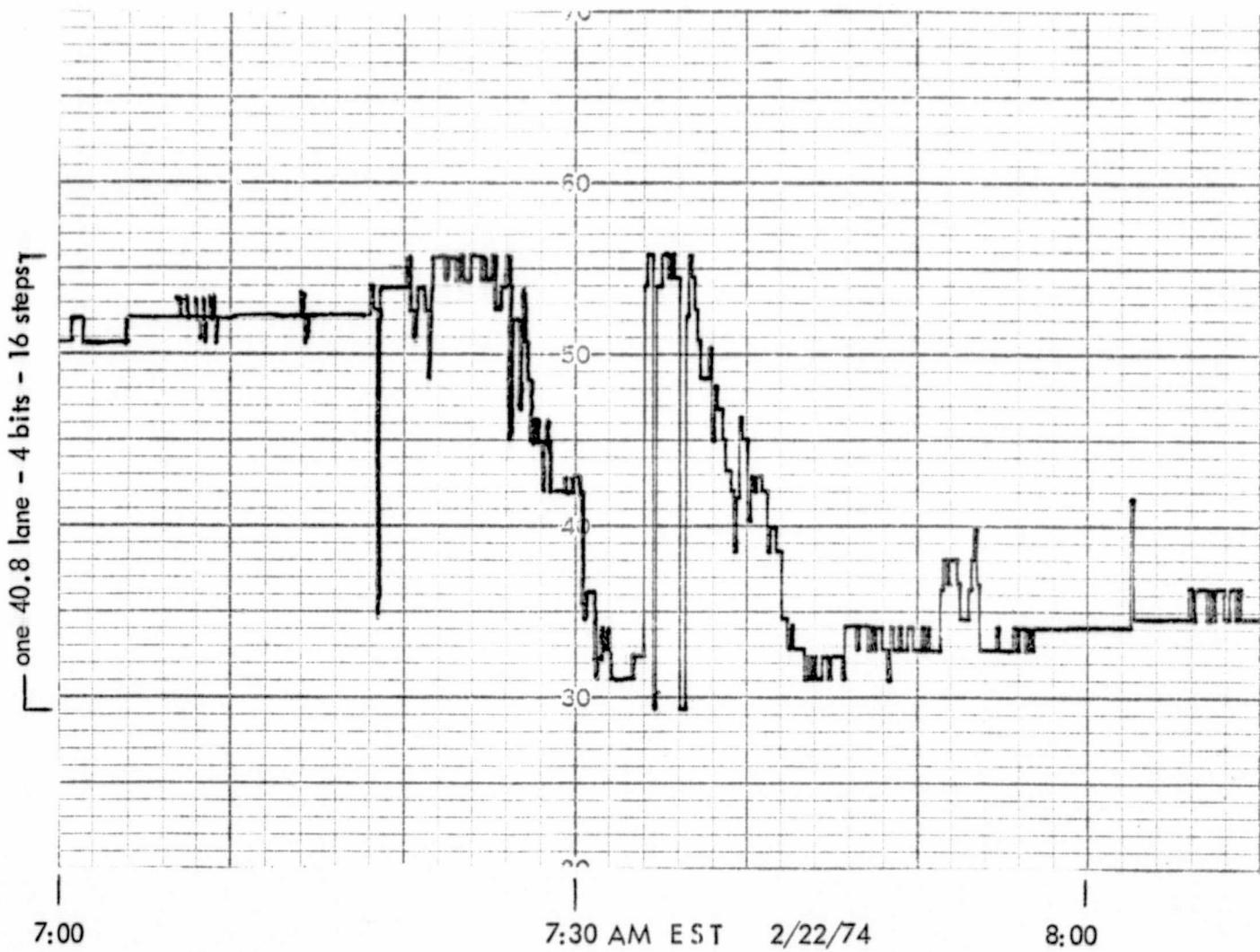
D CHANNEL VS NOISY REFERENCE, OFFSET  $5 \times 10^{-7}$



40.8 KHz Phase Detector D/A Output

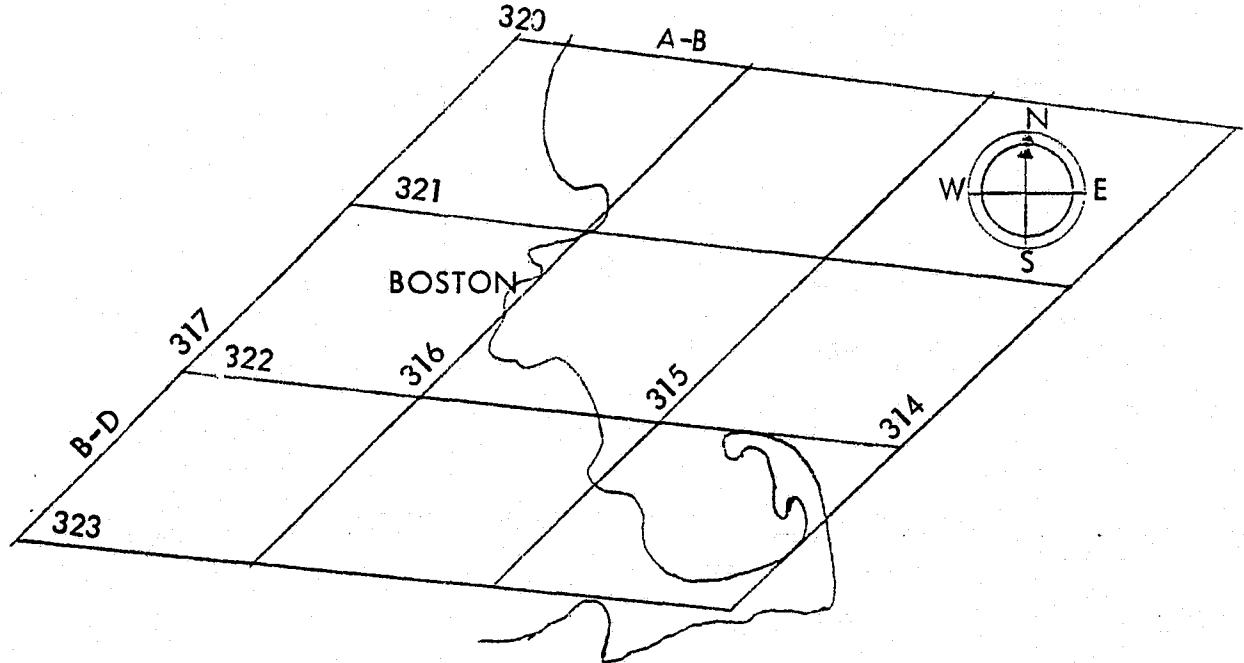
SIMULATED ONE-WAY RANGING

FIGURE 27

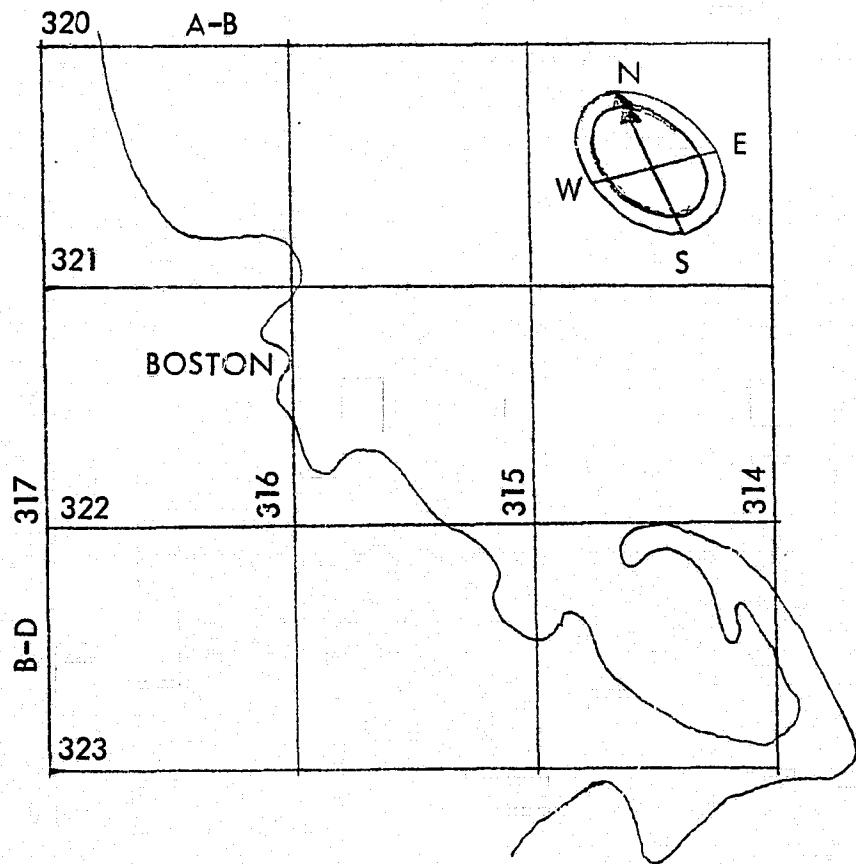


(Range of D with respect to Ohio)  
SUNRISE 40.8 KHz LANE SHIFT

FIGURE 28



NORMAL OMEGA COORDINATES, 3.4 KHz LANES



RECTANGULAR OMEGA COORDINATES, 3.4 KHz LANES

Figure 29